UNDERGROUND CORROSION OF WATER PIPES IN CANADIAN CITIES
CASE: THE CITY OF CALGARY
FINAL REPORT

by

Caproco Corrosion Prevention Ltd.
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UNDERGROUND CORROSION OF WATER PIPES IN CANADIAN CITIES CASE: THE CITY OF CALGARY FINAL REPORT

1. BACKGROUND

Corrosion failures of underground water pipes in Canadian cities are becoming a very serious problem, of considerable financial consequence. As of 1981, there was very little information in the open literature regarding Canadian experience. Accordingly, the Canada Centre for Mineral and Energy Technology (CANMET) of Energy, Mines and Resources Canada, Ottawa, decided to support research aimed at defining more clearly the extent of the problem and the failure mechanisms involved. In September 1981 a contract was awarded to Caproco Corrosion Prevention Ltd. of Edmonton, Alberta, to study water pipe performance in the City of Calgary, which was known to be experiencing a relatively large number of failures.

2. WORK PLAN

The work was divided into the three phases described below.

Phase I*: An interpretive history of the frequency and cause of water pipe failures was prepared based on data from over 13,500 failure reports (1956-80) filed by the City of Calgary Waterworks Division.

Phase II*: Seventeen samples of the water main failures occurring currently were collected in 1982/83 along with soil samples at the pipe depth. A complete failure analysis including chemistry, mechanical properties, metallurgy of pipe and chemistry of the soil was performed on the ten pipe failures considered to be most representative.

Phase III: is covered by this report, which is designed for wide distribution and contains a synthesis of Phases I and II with a literature survey, analysis of the results, and recommendations. Canadian manufacturers of cast iron and ductile iron pipes and the standards those pipes must meet are listed. Photographs of typical failures of water mains are presented.

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* Internal Reports: Underground Corrosion of Water Pipes in Canadian Cities, Case: The City of Calgary
Phase I: Study of the Subject (Volume I-III), April 28, 1982.
Phase II: Typical Water Pipe Failures and Failure Analysis, February 7, 1983.

3. PROCEDURES, SOURCES, REFERENCES

Data required to complete Phase I of the study was gathered from the City of Calgary files, documents and maps, as well as through meetings and discussions with the technical staff of the Waterworks Division. A condensed summary of Phase I of the study is given in Appendix A.

Current (1982 - 83) failed pipe and soil samples for Phase II were collected by Caproco at sites within Calgary city limits. Stress was put on collection of samples of failed pipe from different city sections, as well as different types of failure, pipe material and size, and age (time in the soil). Each pipe sample was selected for detailed chemical, mechanical and metallurgical evaluation or only qualitatively examined. In all, seventeen (17) pipe failures and soil samples were collected, and the most representative ten (10) analyzed in detail. Hardy Associates (1978) Ltd.* performed chemical, mechanical and metallurgical analyses of the failed pipes, and analyzed the soil samples. A condensed summary of Phase II findings is given in Appendix B.

Photographs of typical failures of cast and ductile iron water pipes, service saddles, and some fittings are reproduced in the photographs in Appendix C.

Literature references and other sources reviewed and analyzed for completion of the study, relevant specifications, and Canadian water pipe manufacturers have been listed in Appendix D.

4. APPENDICES

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- A.2 Failure Frequency vs Pipe Material
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- A.5 Mechanism of Water Pipe Failures
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* Name changed (March 1983) to: Non Destructive Inspection Ltd.

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B.1 Collection and Evaluation of Samples
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5. REVIEW AND DISCUSSION OF FINDINGS

5.1 General

There were 2750 km of buried water distribution pipes in Calgary at the end of 1980. The system consisted of pipes made of cast iron (45%), ductile iron (42%), steel (3.5%), asbestos-cement (2.5%), concrete (5.4%), polyvinyl chloride (1.7%) and polyethylene (0.2%).

Review of more than 13,500 failure reports revealed that failures in the water distribution system occur most frequently in pipes. Ninety-two percent of the failures that appeared over a period of twenty-five years (1956 to 1980) were associated with failures of pipes; service saddles accounted for 6.2% of the failures while the remaining cases of failure (1.8%) concerned such fittings as valves, hydrants, service rods and the like.

The average break frequency was 46/100 km per year over a period of five years ending in 1980, while during the period 1956 - 1980 the highest annual rate, in 1979, was 60 breaks/100 km. Analysis of the statistics between 1956 and 1980 revealed that corrosion was an operative factor in about 60% of the failures, while mechanical factors played a role in about 90% of the failures. It is assumed, however, that in many less obvious cases, corrosion was not recongnized as the primary reason for the failure and the actual number of corrosion-induced cracks, splits, etc., was higher than shown by the statistics.

Prior to this study, a special investigation of water main corrosion was commissioned by the City of Calgary in 1975 (1). This has resulted in the implementation of a more effective corrosion control program which has been in force since.

Other sources - most of which are not readily available - deal with the corrosion of water mains. Stress is laid on the extent of this problem and resulting maintenance and replacement costs in many cities across Canada (2-6).

Particularly critical is the situation in Winnipeg where there were 2,200 water main failures during each of the last three years (1980 - 1982), i.e., 100 failures per 100 kilometers of installed pipe (5).

The present study makes it clear that water main failures have been a problem in Canada for at least 25 years. Information published in the last thirty years (7-10) and even earlier (11-13) describe various cases of water main failures and point to corrosion of pipes as one of the most important reasons for the leaks and breaks.

5.2 Failures of Cast Iron Pipes

Until 1963, about 90% of the pressure water pipes in Calgary were made of cast (gray) iron with the balance made of steel, asbestos-cement and cement (Table A-1).

Since 1963, the cast iron pipes have been gradually replaced by pipes of different materials, mostly ductile iron. The use of cast iron pipes for new lines was suspended completely in 1968. As of 1980, there were still 1236 km of cast iron water mains in Calgary, i.e., 45% of the total installed length. However, the length of cast iron piping in the ground has been gradually decreasing because sections of the mains which have deteriorated are being replaced with pipes made of other materials.

Failure frequency for buried cast iron pipes showed a linear increase between 1956 and 1969, then stabilized at an annual rate of approximately 50 failures/100 km of pipe to 1980 (Tables A-2 and A-3; Fig. A-1).

During 1979 and 1980, total lengths of buried cast and ductile iron were sufficiently similar to permit rough comparisons of failure mechanism on the basis of Tables A-10 and A-11. These data indicate that purely mechanical failures of cast iron pipe outnumbered those shown by ductile iron by about 2.5 to 1; such failures are more frequent in the winter than in the summer

months. Corrosion-related failures of cast iron occur at about the same rate throughout the year and tend to be less frequent in cast than in ductile iron (see also Fig. A-3)

It has been found that cast iron pipes corroded to perforation of the wall by pitting, or were subject to relatively slow graphitic corrosion in which the iron corrodes, while the graphite remains in place. The pipe wall is thereby weakened, and much more prone to mechanical failure.

Typical failures of cast iron pipes in Calgary are characterized by a large leak in the pipe wall related either to pitting attack (Fig. C-1) along graphite flake/ferrite interface (or iron carbide containing regions), to pitting and break failure (Fig. C-2), or to graphitic corrosion.

In the latter case, there may be little or no change in the appearance of the pipe, but the metal has lost its strength. When there is an increase in water pressure, or when an external stress appears, the pipe may break (crack, split) at spots weakened by graphitization (Fig. C-3).

In recent (1982 - 83) pipe failures in Calgary, the average rate of pitting corrosion of cast iron was 0.41 mm/year (Tables B-2 and B-3). Pitting corrosion rates for cast iron have been found to increase with decreasing soil resistivity at the failure location (Fig. B-1).

Although corrosion was the major failure mode of the cast iron pipe failures subjected to metallurgical evaluation, in two out of five cases it has been found that the failures also had mechanical aspects derived from substandard mechanical properties of the material (Tables B-4 and B-6).

Corrosion and other failures of cast iron pipes have been described in several references (7-13). Long-term performance of cast iron and other metal pipes in soil, based on extensive studies conducted by the N.B.S.,* has been reported by Romanoff (14). Observations and conclusions of these references are in most cases similar to those noticed for Calgary.

5.3 Failures of Ductile Iron Pipes

Ductile iron (nodular iron) is a type of cast iron in which treatments by Mg (or Ce) has converted the graphite into spheroidal form. Mechanical properties are considerably improved as compared with cast iron (Tables B-4 and B-5).

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* National Bureau of Standards, U.S.A.

Ductile iron pipes were introduced into the Calgary water distribution system in 1963 and by 1968 were totally replacing cast iron in new installations. By the end of 1980, there were 1144 km of ductile iron pipes in the ground, i.e., 41.6% of all pipes in service (Table A-1).

Despite the initial expectation of being corrosion-resistant without additional protection, ductile iron exhibited pitting attack in the aggressive soil typical of many parts of Calgary.

A rapid increase in the failure frequency for buried ductile iron pipes was noticed a few years after these pipes were introduced in Calgary. The increase has been from 0.5 failures per 100 km of pipe in 1970 to 29 failures in 1980 (Tables A-2 and A-3, Fig. A-1). Such kinetics of leak frequency with time have been reported to be typical for corrosion failures (10). Failures of ductile pipe examined have typically been caused by corrosion pitting, resulting in complete perforation of the pipe wall (Fig. C-4).

It should be kept in mind, however, that the City of Calgary has reported many mechanical failures of ductile iron pipes (Tables A-10 and A-11). The mechanical properties of most of the ductile iron pipes examined appeared to be below standard, which would favour this type of failure (Tables B-4 and B-6). The relatively good performance of steel pipes (Table A-3) also suggests the importance of good mechanical properties.

Formation of pits seems to be random, i.e. unrelated to any specific place on the pipe circumference or along the pipe length. Observations indicate, however, that initiation of pits has been more frequent in the vicinity of the un-insulated multimetal (bronze/ductile iron/steel) service saddles joining the pipe to a copper service line.

Analysis of the data indicates that ductile iron pipes are at least equally prone to corrosion-related failures in Calgary soil as cast iron pipes, despite the much shorter period of the former in the ground (Tables A-10 and A-11).

In recent (1982 - 83) pipe failures in Calgary, the average pitting corrosion rate for ductile iron was 1.11 mm/year, almost three times higher than that observed for cast iron. The pitting rates were more strongly dependent on soil conductivity than rates for cast iron pipes (Fig. B-1). As discussed below, the rates of corrosion pitting determined for ductile iron in Calgary fall within the range found by others (18).

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Basic information about properties and expected performance of ductile iron has been published by LaQue (15, 16). This was supplemented by the findings in extensive tests initiated and conducted by N.B.S. from 1958 and described by Romanoff (17) and Gerhold (18). Long-term NBS tests revealed that pitting corrosion rates for ductile iron pipes in heavy clay soil, varied between 0.5 and 1.5 mm/year and that kinetics were linear to perforation of the pipe wall.

A history of a new ductile iron water main system in a suburb of Milwaukee, Wisconsin, which began to experience severe external corrosion failures within six years in low resistivity (ρ = 500 to 1500 ohm-cm) clay soil has been described (19).

The pit depth vs time equation given below was developed and used by the N.B.S. in their early corrosion studies of leaks in pipelines (20).

$$P = K \cdot T^n$$

where P = the depth of the deepest pit at time T,
K, n = constants depending on the soil characteristics (value of n: $0<n<1$).

The above equation or a modified version has been used for leak prediction in buried ductile iron or other metallic pipe (4, 21, 22). In the light of information presented in the references (17 - 19) and confirmed by our findings for the City of Calgary, this equation seems to be of little value for prediciton of pitting corrosion of ductile iron in poorly aerated, low resistivity, corrosive soil.

Studies of corrosion weight losses in soil environments in Europe have inspired attempts to determine the kinetics of corrosion attack on pipes made of ductile iron (23, 24). So far, the results appear to be inconsistent (25).

5.4 Failures of Service Saddles

Although various fittings of water service mains fail, the most significant failures have occurred in service saddles, which account for approximately 6% of all main failures in Calgary between 1956 and 1980 (Table A-2).

House water lines (services) are connected with the mains by means of service saddles. In the original design used in Calgary for years, a service saddle made of ductile iron was connected to the main with a steel tie-rod and joined to the copper

service line through a brass main cock. This variety of metals directly connected together created a very active galvanic cell in a conductive (low resistivity) soil environment resulting in numerous corrosion failures of the saddles, or of the mains in close proximity to the service connection (Fig. C-5).

About 1975, after an extensive corrosion prevention program of water mains had been initiated by the City of Calgary Waterworks Divison, the saddle was redesigned. Dielectric insulation was inserted to part dissimilar metals, and the saddle itself was well coated.

Bronze saddles with a Type 304 stainless steel holding band and rubber insulating padding are used in Calgary at present, and though little service experience has been gained they are assumed to be well designed and corrosion resistant.

It should be stressed, however, that improperly designed multimetal saddles are still manufactured and used in aggressive soils in Canada. For example, in 1982, a series of mains failures in a condominium in Edmonton were traced to excessive corrosion at service saddles which had only been underground for 5 years. The saddles were found to be of ductile iron, steel, and bronze and were being used to connect 6-inch ductile iron pipes with copper service lines; incompatible metals had not been isolated electrically by insulators (26).

On the other hand, the City of Edmonton which adopted all-bronze saddles as a standard for the city installations more than twenty years ago, has experienced very few corrosion problems in the saddles.*

5.5 Environment

5.5.1 Corrosivity of Soil

Analysis of the statistical data provided by the City of Calgary, as well as chemical analysis of the soil samples collected at the failed pipe depth, indicate that except for some areas of sand along the river, the soil in Calgary is mostly clay and silty-clay (Tables A-5 and B-7).

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*A condominium, as a private property, may or may not adopt the City specifications.

Resistivity of the soil sampled at sites where the lengths of failed water pipes were collected varied from 560 to 4300 ohm-cm, with thirteen out of seventeen samples having resistivity lower than 1000 ohm-cm. These values are compatible with the statistical data of soil resistivity in most parts of Calgary except for soil along the river, where the resistivity is much higher (Tables A-4 and B-2).

Roughly 70% of more than 13,500 pipe and fitting failures experienced in Calgary between 1956 and 1980 took place in clay and silty-clay soil while less than 11% of the failures were experienced in soil containing gravel, sand and silt as the prevailing constituents (Table A-5).

The most frequently used criterion of soil corrosivity is soil resistivity, which is convenient and easy to determine in the field measurement. Soils with high electrical conductance (low resistivity) are, as a rule, corrosive.

On the other hand, the functioning of corrosion cells formed on the metal surface is not determined completely by the electrical properties of the soil. Such important properties of the soil as degree of aeration, amount of moisture, sand content, pH, homogeneity, mineral content and presence of some bacteria affect the corrosion cells to a great extent.

Because of the foregoing complexities, there have been attempts to determine supplementary criteria for appraisal of soil and other conditions that affect the corrosion rate of buried pipes. One such procedure is appended to ANSI A21.5-1972 (AWWA C105-72) Standard.*

According to soil corrosivity criteria adopted for the present study after Baeckman and Schwenk (27), all analyzed samples of Calgary soil fall into the category "corrosive", except for one sample which was rated "very corrosive" (Table B-9).

More details about various factors and soil constituents affecting the resistivity of soils have also been reported (28-33).

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* Appendix A (not part of the standard, for information only): Notes on Procedures for Soil Survey Tests and Observations and Their Interpretation to Determine Whether Polyethylene Encasement Should Be Used.

5.5.2 Temperature Variations

A large majority of the pipe failures in Calgary occurred in winter months when the temperature of water and soil is at a minimum. Between 1975 and 1980 the maximum monthly failure rate during the cold months (November to March) was about five times the minimum failure rate in the summer months (June to September) (Table A-7, Fig. A-2).

According to Morris (9), as the ground water temperature begins to drop in the fall, various stresses may develop in ferrous pipe. Stress is particularily high when the temperature drop approaches 4°C, and the water starts swelling. As the earth temperature drops, it imposes another stress within the pipe. Below freezing point, the frost heave adds to the pipe stress.

The above stresses and the earth load may cause the initial stress to more than double and eliminate the pipe safety margin. If the pipe is under stress from another source or is weakened by corrosion (pitting, graphitization or both), a rupture may occur (See: Fig. C-2).

A maximum in the number of failures in Calgary seems to occur, when the temperature drops to extreme minimum in a few consecutive months, and/or if there is little rainfall over a longer period preceeding the maximum (Fig. A-2, Table A-8 and A-9).

5.5.3 Corrosion Inside Pipes

Sections of cast and ductile pipes examined have been either bare inside or coated with cement-mortar lining.

Except for one case of graphitization of unlined cast iron pipe (Table B-1, Sample #17), no significant corrosion was detected on the inside surface of pipes.

A tendency for accumulation of thin and uniform deposits on all inside pipe surfaces has been noticed. It is assumed that this mineral scale protects the pipe interior against corrosion by service water.

5.6 Pipe Coatings

Statistical data concerning the coating used for protection of water mains in Calgary are incomplete and offer only limited information as to the type of coatings used for protection of pipes between 1956 and 1980.

In most cases cast and ductile iron pipes were buried bare or with a thin bituminous coating having no protective value and used for aesthetics only. In the 60's and 70's, water lines were laid in soil wrapped with loose plastic (polyethylene) film. In the 70's, epoxy coating, adhesive tape, and more recently, an extruded high density polyethylene coating, have also been used for pipe protection.

The latter is the only coating currently approved by the City of Calgary for protection of ductile iron pipes; cold applied laminate tape and epoxy coating, both fusion-bonded and 100% solid thermosetting liquid epoxy, are accepted for protection of the valves, tees and other fittings of complex configuration.

Recently failed (1982 - 83) cast and ductile iron pipes obtained in this study were coated with a bituminous substance and in some cases wrapped in loose polyethylene film. Whether wrapped or without any protection, the bituminous layer has been found to be severely deteriorated and the pipes corroded in a similar manner (Fig. C-6).

In another study (1) conducted for the City of Calgary in 1975, it was found in several cases that polyethylene wrap was not protective, and wrapped pipes and fittings were severely corroded.

Also, tests cited in one of the references indicate that loose polyethylene film has not been a reliable corrosion prevention barrier (34). The ineffectiveness of polyethylene wrap observed in the present and earlier studies contradicts the information published (35, 36) and the recommendations issued by CIPRA* and implemented as a Standard**.

Polyethylene wrap might also shield water mains such that cathodic protection cannot be effectively applied.

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* Cast Iron Pipe Research Association (U.S.A.)

** ANSI A21.5-1972 (AWWA C105-72) Standard: Polyethylene Encasement for Gray and Ductile Cast Iron Piping for Water and Other Liquids.

New coating systems for protection of ductile iron pipes in aggressive soil have appeared relatively recently on the market. Promising preliminary results have been published on the performance of sprayed zinc coating sealed with coal tar (37, 38). Another promising product is fiber reinforced polymer-concrete coating, introduced a few years ago in Canada (39). More information about long-term performance and economics of these coatings is required, however.

5.7 Non-Metal Pipes

At the end of 1980, non-metal pipes accounted for about 10% of the length of the water mains in Calgary. There were 52.7 km of thermoplastic pipe (PVC, PE) first introduced in 1970; the failure rate has been very low. Failure frequency in the 149.4 km of cement pipe has also been very low, but asbestos-cement pipes have been failing at about the same rate as ductile iron pipes (Tables A-1, A-2 and A-3).

It appears that despite relatively long experience* and good performance in soil environment, the use of thermoplastic is rather limited to date, not only in Calgary but elsewhere in Canada. Long-term studies reported by the A.W.W.A. (41) indicate that the useful life of plastic pipe should equal that expected for iron and steel pipe, if the recommended stress for the material is not exceeded.

Thermoplastic pipes have been performing very well in the corrosive Calgary soil. Its good performance seems to warrant expanded use and further testing.

6. SUMMARY AND CONCLUSIONS FROM STUDY

1. There were an average of 46 failures per 100 km of water mains in the 2750 km water distribution system in Calgary in 1980. The most common sources of failure in the system were pipes (92%), service saddles (6.2%), and various other fittings (1.8%).

2. Statistical data (1956 - 1980) indicates that about 60% of the mains failures were associated with corrosion. Examination of current (1982 - 83) pipe failures showed that corrosion always played an important role.

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* The first commercial production of thermoplastic pipe started in 1941 (U.S.A.); it was valued at $50 million in 1957 and at $187 million in 1968 (40).

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3. Statistical data (1956 - 80) indicates that mechanical factors (splits, cracks, etc.) were an operative factor in about 90% of the pipe failures. However, in current (1982 - 83) failures examined, mechanical factors only played a role in two cast iron pipes. The relationship between pipe toughness and performance warrants further investigation.

4. Corrosion of cast iron pipes may appear as a localized attack in the form of pitting, leading to perforation of the pipe wall. Alternatively, cast iron pipes may exhibit graphitic corrosion, i.e., a selective leaching of the ferrous matrix, resulting in loss of the pipe strength and possibly to pipe rupture. The two forms of corrosion attack are sometimes combined.

   Substandard tensile strength of the material has contributed to cast pipe failures.

   The average pitting corrosion rate of cast iron in typical soil within the Calgary city limits was found to be 0.41 mm/year.

5. Ductile iron pipes corrode by localized pitting attack, leading in some cases to pipe wall penetration. In recent (1982 - 83) failures examined, there was no indication that mechanical factors were operative, through most of the ductile iron pipes showed substandard mechanical properties. Statistical data reveal, however, that there were failures of ductile iron mains due to mechanical reasons.

   Failure frequency as a function of time has been exponential for ductile iron, and such kinetics are typical for pitting corrosion of ferrous materials.

   The average pitting corrosion rate for ductile iron pipes in typical Calgary soil was 1.11 mm/year.

6. Underground deterioration and failure of improperly designed multimetal (bronze, steel, cast or ductile iron) service saddles, in which incompatible metals have not been electrically isolated, have been due to galvanic corrosion of the ferrous parts.

7. Soil in Calgary is mostly wet clay or silty clay containing a considerable amount of dissolved solids. Soil samples taken in connection with recent (1982 - 83) pipe failures showed resistivities within the range 500 - 5000 ohm-cm.

A linear relationship between pitting corrosion rate and soil resistivity has been found for buried cast and ductile iron pipes. Ductile iron shows a steeper slope than cast iron.

Taken as corrosivity criteria, chemical constituents and physical properties of the soil indicate that soil in Calgary (except for sand and gravel along the river) is corrosive or very corrosive.

8. Pipe failures in the cold months (October to March) outnumber pipe failures in the summer months by up to 5:1.

   Mechanically-induced failures of pipes are more frequent in winter than in summer months, with cast iron failing more often than ductile iron pipes.

   The frequency of corrosion-related failures for both cast and ductile iron is relatively stable throughout the year.

9. Among 17 recent (1982 - 83) pipe failures examined, only one showed significant inside-pipe corrosion.

10. In Calgary, until the late '70's, both cast and ductile iron pipes were placed in the soil essentially uncoated, a thin bituminous coating being applied for aesthetics only.

    In a number of cases, pipes and fittings were wrapped (encased) in loose polyethylene (black) film prior to burial. No evidence has been found that pipes protected in this way corroded at a lower rate than those which were placed in the soil without a wrap.

11. Experience to date indicates:

    a) Effective protection of ferrous metal mains in aggressive Calgary soil has been achieved with quality coating combined with cathodic protection.

    b) Highly satisfactory performance of the thermoplastic pipes (PVC, PE) in typical Calgary soil.

12. Cement pipes have been performing very well in the aggressive Calgary soil. Most failures experienced with asbestos-cement pipes in recent years are probably related to deterioration and failure of the metallic fittings used with these pipes.

7. RECOMMENDATIONS FOR FURTHER INVESTIGATIONS

In the following paragraphs, recommendations are made for further research on the water pipe problem in Canadian cities. Results of the proposed research should indicate ways of improving water pipe performance, and result in lower pipe maintenance costs.

1. Determine if old, buried, and graphitically corroded cast iron pipes and fittings can be protected against progressive deterioration by applying cathodic protection.

2. Determine the technical and economic advantages of water main life extension by applying cathodic protection versus gradual replacement of the lines with new, well-protected or corrosion-resistant pipes and fittings, or by installation of plastic inserts inside corroding pipes.

3. Demonstrate optimum protective coatings for ductile iron underground systems as a function of soil properties. The coatings should be compatible with cathodic protection.

4. Determine the feasibility of non-metal pipes for water distribution systems in Canadian cities.

5. Determine criteria for evaluation of soil corrosivity involving not only soil resistivity, but other soil parameters including soil chemical constituents.

6. Determine to what extent unprotected copper service pipes are susceptible to corrosion in aggressive soils found in certain areas in Canada.

   There are indications that copper may corrode excessively in certain soils when it is electrically separated from ferrous pipes or fittings, which will normally protect copper by providing sacrificial cathodic protection.

7. Determine if the service saddles available at present are resistant enough for long service in corrosive soil environments.

CAPROCO CORROSION PREVENTION LTD.

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Any data presented, opinions, findings, conclusions or recommendations expressed in this report are those of the author and do not necessarily reflect the views of CANMET.

The author is indebted for PMRL CANMET for permission to publish this work.

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J. A. Jakobs

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APPENDIX A

WATER MAIN FAILURES, PERIOD 1956 - 1980

(Statistical Data)

SECTIONS

A-1 INTRODUCTION

A-2 FAILURE FREQUENCY vs PIPE MATERIAL

A-3 NUMBER OF FAILURES PER LENGTH OF INSTALLED PIPE

A-4 TOPOGRAPHY OF FAILURES vs RESISTIVITY AND TYPE OF SOIL

A-5 MECHANISM OF WATER PIPE FAILURES

A-6 FAILURE FREQUENCY vs MONTH OF THE YEAR

A-7 FAILURE MECHANISM vs MONTH OF THE YEAR

TABLES A-1 to A-11

FIGURES A-1 to A-3

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A-1 INTRODUCTION

The objective of the work summarized in this Appendix was to determine the frequency and cause of water pipe failures in Calgary from statistical records (i.e., pipe failure reports) made available by the City of Calgary. The records covering the twenty-five year period (1956 to 1980) were reviewed and analyzed. There were 13,561 water distribution system failures in the period under consideration, with the highest yearly number of 1,541 failures registered in 1979.

There were approximately 2,500 km of water pipes at the end of 1980. The water mains were made principally of cast (CI) and ductile (DI) iron, but to a lesser extent of steel (S), asbestos-cement (AC), cement (C), polyvinyl chloride (PVC) and polyethylene (PE).

The length of piping of each of these materials in the Calgary water distribution system is shown for the period 1956 to 1980 in Table A-1.

A-2 FAILURE FREQUENCY vs PIPE MATERIAL

Water main failures were divided into three categories: failure of the pipe itself, failure of the tapping saddle, and failure of the various pipe fittings. The pipe failures were also analyzed according to pipe material. Failure frequency in terms of the above categories and pipe material is presented in Table A-2.

The first of two extracts from Table A-2 shows that pipe failures were of the greatest technical significance by far.

Category of Failure	Number of Failures	%
Water Transmission Pipes	12,470	92.0
Service Saddles	844	6.2
Other (valves, hydrants, service rods, etc.)	247	1.8
Total	13,561	100.0

As shown below, there were 11,329 cast and ductile iron pipe failures, i.e., above 90% of all failures.

Material of Pipe	Number of Pipe Failures	%
Cast Iron	10,101	81.0
Ductile Iron	1,228	9.8
Carbon Steel	221	1.8
Asbestos-Cement	96	0.8
Cement	16	0.1
PVC	1	0.0
Unidentified	807	6.5
Total	12,470	100.0

A-3 NUMBER OF FAILURES PER LENGTH OF INSTALLED PIPE

The number of failures per year for 100 km length of each installed pipe material is given in Table A-3.

Failure frequency for cast iron pipes was consistently higher than for ductile iron pipes for the period investigated. In the period 1970 - 80, the average number of failures per year for CI stabilized at about 50 per 100 km of installed pipes.

There has been, however, a significant and continuous increase of ductile iron failure frequency between 1970 and 1980 from 0.5 to 29 per 100 km of pipe per year.

The number of failures per length of installed pipe for both CI and DI from 1956 - 80 is shown graphically in Fig. A-1.

The rate of failure per length of installed steel pipes has been declining steadily between 1956 and 1980.

The number of failures per length installed was very low for all pipes made of synthetic materials (PVC, PE) and for concrete pipes. The rate of failure for asbestos-cement pipes was exceptionally high between 1978 and 1980 as compared to that in previous years.*

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* There is a probability that several failures of the AC pipes attributed to the pipe material were actually associated with corrosion of the multimetal service saddles. There is a proven case where water leakage from the corroded service saddle has caused removal of the sand backfill and resulted in the pipe failure (Failure No. 16, Appendix B).

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A-4 TOPOGRAPHY OF FAILURES VS. RESISTIVITY AND TYPE OF SOIL

Soil resistivity within the city limits has been occasionally measured by the Waterworks Division and registered according to the point of measurement on the city section maps. The resistivity has been measured and registered so far at thousands of locations all over the city.

Soil resistivity data from thirteen (13) randomly selected sections, each approximate 2.6 km^2 in area, are summarized in Table A-4 which also shows the number of failures in each section in 1979. The relationship between the frequency of water main failures and the type of soil has been summarized in Table A-5.

Comparison of the failure distribution with type of soil and resistivity data indicates that there is a higher frequency of water main failures in city areas where the resistivity of soil is low. Low resistivity clay and silty-clay soil appear to be the most corrosive to both cast and ductile iron pipes and fittings. City areas along the Bow River, where sandy soil of higher resistivity prevails, are much less subject to water main failures.

A-5 MECHANISM OF WATER PIPE FAILURES

Statistical information related to the mechanism of the water pipe failures from 1956 to 1980 in Calgary has been summarized in Table A-6.

The data indicate that about 60% of the pipe failures were either due solely to corrosion, or corrosion was a contributing factor. Mechanical factors were still more important, being an operative factor in about 90% of the failures.

A-6 FAILURE FREQUENCY vs MONTH OF THE YEAR

Month-to-month occurrence of water main failures over the period 1956 to 1980 has been summarized in Table A-7. It is evident that for the whole period, the number of pipe failures was much higher in winter than in summer months with the lowest level of failures between June and September. This is illustrated in Figure A-2.

Temperature range and rainfall data for each month of the year in Calgary have been tabulated for comparison with water main failure occurrence. This data is presented in Tables A-8 and A-9.

A-7 FAILURE MECHANISM vs MONTH OF THE YEAR

Month-to-month failures of cast and ductile iron pipe for 1979 and 1980 have been summarized and divided into two categories: (1) solely mechanical; (ii) corrosion-related. This data is given in Tables A-10 and A-11 and is presented as a graph in Figure A-3.

Pipe failures show the following trends:

a) Corrosion-related failure frequency is relatively stable throughout the year.

b) Mechanical failures are most frequent in winter and least frequent in summer.

c) Corrosion-related failures are more numerous for ductile iron than cast iron pipes, despite the shorter period of the ductile iron pipes in the ground.

d) Mechanical failures of cast iron pipes outnumber those for ductile iron pipes by a ratio of about 2.5/1.

TABLE A-1

LENGTH OF WATER MAINS BY PIPE MATERIAL*

Year	Length of Pipe at Year End (km)							Total Length (km)
	CI	DI	S	AC	C	PE	PVC	
1956	607.2		71.9	5.6	17.4			702.1
1957	654.0		66.1	7.0	18.8			745.9
1958	750.5		55.2	13.8	18.8			838.3
1959	812.5		52.0	15.8	22.7			903.0
1960	866.9		43.2	18.8	29.2			958.2
1961	919.2		36.8	25.2	29.2			1010.4
1962	1033.0		38.0	26.3	36.8			1134.2
1963	1089.2	3.5**	38.0	30.3	37.1			1198.2
1964	1167.1	6.8	40.1	32.9	39.4			1286.3
1965	1212.3	15.2	42.1	32.9	40.1			1342.6
1966	1238.0	21.8	43.9	32.9	45.4			1381.9
1967	1274.6	30.5	45.1	32.9	49.8			1432.9
1968	1277.5	84.8	48.0	32.9	57.5			1500.8
1969	1276.1	137.1	50.5	32.9	58.5			1555.1
1970	1275.3	209.9	52.1	33.6	63.1		0.1**	1634.1
1971	1272.0	281.3	56.9	34.5	63.7		0.1	1708.5
1972	1269.8	368.5	74.0	33.4	67.4		0.1	1813.2
1973	1268.1	466.4	78.2	34.5	76.6		0.1	1923.8
1974	1266.6	552.1	80.2	47.9	88.8		0.2	2035.8
1975	1262.5	624.6	83.0	57.5	100.4		0.2	2128.2
1976	1257.5	701.4	87.1	64.7	109.9		1.6	2221.9
1977	1250.4	807.6	89.4	69.4	120.5	2.6**	4.4	2344.4
1978	1244.3	914.3	93.6	69.4	128.6	2.6	11.3	2464.1
1979	1239.9	1058.0	94.3	69.5	131.5	6.5	16.8	2616.6
1980	1236.3	1144.6	95.6	69.3	149.4	6.7	46.0	2747.9

* See text for definition of symbols.
** Beginning of use.

TABLE A-2

FAILURE FREQUENCY OF WATER PIPES (BY MATERIAL) AND OTHER FAILURES

Year	Pipe Material								Other than Pipe		
	CI	DI	S	AC	C	PVC	PE	Unknown	Various Fittings	Service Saddle	Total
1956	93		34					97	0		153
1957	80		20					3	4	1	108
1958	34		22	1				1	8	0	66
1959	61		9					16	8	0	94
1960	95		18	3				4	2	0	122
1961	119		4	1				16	4	0	144
1962	225		12	3				32	11	0	283
1963	247		10	3				30	8	2	300
1964	283		6	1				17	2	0	309
1965	383		3					18	7	0	411
1966	385		7	3	2			30	19	0	456
1967	336	1	6	2	1			30	17	0	393
1968	351	1	4					7	6	0	369
1969	714	1	3					5	6	0	729
1970	468	1	5	2				2	4	0	482
1971	504	3	7	1				1	11	2	529
1972	685	4	4	2	2			1	7	0	705
1973	571	15	2	6				2	5	0	601
1974	729	24	9	1	1			2	7	6	778
1975	709	68	5		3			1	4	3	787
1976	673	82	0					24	6	3	797
1977	514	140	5	2	3		0	96	11	111	882
1978	675	212	7	25			0	136	19	211	1285
1979	688	344	4	19	2		0	206	31	244	1541
1980	475	332	7	21	2	1	0	118	20	161	1237
Total	10,101	1,228	221	96	16	1	0	807	247	844	13,561

TABLE A-3

NUMBER OF FAILURES PER LENGTH OF INSTALLED PIPE(S) (BY MATERIAL)

Year	Number of Failures per 100 km of Pipe						
	CI	DI	S	AC	C	PE	PVC
1956	15.3	-	47.3	0	0	-	-
1957	12.2	-	30.3	0	0	-	-
1958	4.5	-	39.9	7.3	0	-	-
1959	7.5	-	17.3	0	0	-	-
1960	11.0	-	41.7	16.0	0	-	-
1961	13.0	-	10.9	4.0	0	-	-
1962	21.8	-	31.6	11.4	0	-	-
1963	22.7	0	26.3	9.9	0	-	-
1964	24.3	0	14.9	3.0	0	-	-
1965	31.6	0	7.1	0	0	-	-
1966	31.9	0	15.9	9.1	4.4	-	-
1967	26.4	3.3	13.3	6.1	2.0	-	-
1968	27.5	1.2	8.3	0	0	-	-
1969	56.0	0.7	5.9	0	0	-	-
1970	37.0	0.5	9.6	6.0	0	-	0
1971	39.6	1.1	12.3	3.0	0	-	0
1972	54.0	1.1	5.4	6.0	3.0	-	0
1973	45.0	3.2	2.6	17.4	0	-	0
1974	57.6	4.4	10.0	2.1	1.1	-	0
1975	55.7	10.9	6.0	0	3.1	-	0
1976	53.5	11.7	10.3	0	0	-	0
1977	41.1	17.3	5.6	2.9	2.5	0	0
1978	54.3	23.2	7.5	36.0	0	0	0
1979	55.5	32.5	4.2	27.3	1.5	0	0
1980	38.4	29.0	7.3	30.3	0.7	0	2.2

Note: "-" means material not used
"0" means material in use, no failures

TABLE A-4

RESISTIVITY OF SOIL AND FAILURE OCCURRENCE

(13 Randomly Selected Sections of Calgary)

City Section	Resistivity (ohm-cm) (Most Readings)	Resistivity (ohm-cm) Minimum/Maximum	Number of Failures (Year1979)
22 NE	1000 - 2500	480/ 6600	33
10 SE	1200 - 2500	840/ 4000	38
9 SE	2500 - 3500	1200/ 4400	41
16 SE	2500 - 3500	1720/11200	21
22 SE	3000 - 6000	1200/ 8000	27
15 SE	1800 - 7400	500/ 7600	28
27 NE	1600 - 2000	1000/ 6000	31
10 NE	2000 - 4000	500/16000	34
9 NW	3000 - 6000	1640/22000	19
4 NW	1600 - 6000	200/11200	14
3 NE	1400 - 3000	600/ 5000	20
16 CSW	3500 - 5000	1600/ 8200	12
21 CNW	16000 - 20000	8000/44000	6

Legend: NE = North-East
NW = North-West
SE = South-East
SW = South-West
CSW = Central South West
CNW = Central North West

TABLE A-5

OCCURRENCE OF PIPE AND FITTING FAILURES VS SOIL TYPE

Year	Gravel (1)	Sand (2)	Silty Sand (3)	Silt (4)	Silty Clay (5)	Clay (6)	Other*	Total
1956	33	5	5	2	0	70	38	153
1957	8	3	1	4	1	61	31	108
1958	4	4	1	1	0	38	18	66
1959	12	5	0	1	0	48	28	94
1960	10	2	3	1	0	93	13	122
1961	3	3	2	6	5	88	37	144
1962	11	11	0	2	11	200	48	283
1963	13	10	0	0	0	201	76	300
1964	10	2	0	1	0	229	67	309
1965	33	1	0	1	0	314	62	411
1966	20	6	1	0	1	289	139	456
1967	18	10	0	3	3	282	77	393
1968	11	6	1	1	0	268	82	369
1969	21	8	0	1	0	534	165	729
1970	13	3	0	0	0	361	105	482
1971	29	14	16	2	108	302	58	529
1972	40	6	30	1	94	455	79	705
1973	16	11	25	2	122	370	55	601
1974	26	7	18	2	152	544	29	778
1975	32	12	41	1	206	435	60	787
1976	42	6	28	0	234	363	124	797
1977	42	10	38	0	228	415	149	882
1978	94	21	78	2	349	491	250	1285
1979	169	22	88	5	334	533	390	1541
1980	115	8	64	2	227	472	349	1237
Total	824 (6.1%)	196 (1.4%)	440 (3.2%)	41 (0.3%)	2,075 (15.3%)	7,456 (54.0%)	2,529 (18.6%)	13,561 (100.0%)

* Includes mixtures of soil (two or more types) and unknown soil types.

TABLE A-6

FAILURE MECHANISM IN WATER PIPES*

Period	Mechanical (a)	Corrosion (b)	Mechano-Corrosion (c)	Undefined (d)	Total
1956-1980	4252	501	6887	830	12,470
	(34.1%)	(4.0%)	(55.2%)	(6.7%)	(100.0%)

* Soil-side corrosion in all cases.

Definition of symbols:

(a) Contraction, split, crack
(b) Corrosion (to perforation)
(c) Both mechanical factors and corrosion involved
(d) Includes joint leaks

TABLE A-7

OCCURRENCE OF PIPE FAILURES VS MONTHS OF THE YEAR

Year	Number of Pipe Failures												Year Total
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
1956	11	16	39	7	19	8	9	2	11	3	8	3	136
1957	9	13	11	5	8	8	4	5	15	7	5	13	103
1958	7	5	16	6	12	3	2	0	1	2	4	0	58
1959	2	9	3	4	6	8	5	9	6	4	12	18	86
1960	11	17	7	9	11	7	5	4	3	15	17	14	120
1961	13	7	16	7	0	8	6	6	14	16	23	24	140
1962	30	26	44	22	12	13	3	18	21	27	25	31	272
1963	25	24	24	20	8	18	13	16	17	43	51	31	290
1964	41	24	19	24	18	8	8	6	34	27	49	49	307
1965	43	47	52	36	29	15	16	21	27	28	42	48	404
1966	62	45	35	25	23	12	25	20	19	40	63	68	437
1967	39	34	39	30	16	11	17	9	17	49	51	65	376
1968	61	40	23	17	17	14	11	7	28	42	52	51	363
1969	75	158	138	52	40	27	16	10	23	58	58	68	723
1970	61	49	41	21	26	24	20	14	39	47	68	68	478
1971	75	50	45	40	36	23	24	21	32	49	64	57	516
1972	69	69	112	71	55	35	25	21	36	59	65	81	698
1973	64	57	54	42	44	28	41	25	29	60	77	75	596
1974	96	70	75	73	61	52	33	21	35	47	103	99	765
1975	95	95	95	75	64	63	34	26	20	49	102	62	780
1976	92	67	102	85	72	44	50	38	23	58	87	70	788
1977	95	72	71	67	62	44	28	32	24	57	113	95	760
1978	159	161	108	86	94	63	54	42	32	67	94	95	1,055
1979	137	160	218	115	113	78	59	31	35	69	127	121	1,263
1980	121	92	97	103	83	66	47	47	41	63	72	124	956

TABLE A-8
EXTREME MINIMUM AND MAXIMUM TEMPERATURES* IN CALGARY
1956 - 1980

YEAR	JAN		FEB		MARCH		APRIL		MAY		JUNE		JULY		AUG		SEPT		OCT		NOV		DEC	
	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
1956	-32.2	4.4	-35.0	6.7	-27.8	19.9	-14.4	19.4	-10.0	31.1	1.1	30.6	5.0	31.1	2.8	29.4	-2.2	24.4	-16.7	22.2	-13.9	16.1	-34.4	16.1
1957	-35.6	5.6	-36.7	11.1	-24.4	12.8	-11.1	25.6	- 3.3	24.4	1.1	28.3	5.0	29.4	1.7	25.6	-3.9	27.8	-15.6	26.1	-19.4	15.0	-17.2	15.6
1958	-17.2	13.3	-32.2	11.7	-26.1	7.2	- 5.6	19.4	- 1.7	27.8	0.0	27.8	5.0	30.0	5.0	31.7	-2.8	28.9	- 9.9	25.0	-25.0	15.0	-29.4	13.3
1959	-28.3	9.4	-30.0	13.3	-10.0	15.6	-18.3	20.0	- 6.7	26.7	1.7	31.1	4.4	34.4	2.8	30.0	-4.4	26.1	- 7.2	22.2	-28.9	14.4	-16.7	12.2
1960	-24.4	7.8	-26.7	7.2	-32.2	15.6	-10.0	20.0	- 3.3	27.8	2.8	24.4	4.4	33.9	2.2	29.4	-2.8	30.0	- 6.7	25.6	-21.7	21.1	-27.2	11.7
1961	-24.4	12.2	-23.9	15.6	-19.4	14.4	- 8.9	17.2	- 1.1	28.9	4.4	33.3	5.6	35.0	6.1	34.4	-7.2	25.0	-17.8	25.6	-21.7	17.8	-29.4	10.0
1962	-29.4	13.9	-32.2	13.9	-31.7	10.6	- 7.8	25.0	- 6.1	21.1	2.8	30.0	2.2	28.9	2.8	33.3	-2.2	18.3	- 5.6	26.7	-11.7	18.9	-21.7	16.1
1963	-33.3	13.9	-27.8	13.9	-12.2	18.3	-10.6	22.2	- 3.9	26.7	7.8	29.4	5.6	30.0	5.6	30.6	1.7	30.6	- 8.3	27.8	-32.2	14.4	-31.7	13.9
1964	-29.4	7.8	-13.9	13.9	-28.9	18.3	- 9.4	20.0	- 2.2	27.2	2.2	25.6	4.4	33.3	1.7	31.1	-4.4	27.2	-12.8	27.8	-27.8	18.3	-33.9	9.4
1965	-35.0	13.3	-25.6	11.7	-27.2	10.6	- 8.9	22.2	- 4.4	23.3	-1.1	30.6	6.1	29.4	3.9	31.1	-7.8	21.7	- 6.1	25.6	-30.6	17.8	-32.2	11.7
1966	-35.6	7.2	-25.0	11.1	-20.6	22.2	-18.9	17.2	- 2.8	28.9	1.7	26.1	5.0	27.8	1.7	31.1	-1.7	28.9	-10.0	25.0	-25.6	12.2	-27.2	10.0
1967	-30.6	7.8	-25.0	11.7	-30.6	10.0	-16.1	14.4	- 8.3	25.6	0.0	27.2	2.8	31.1	1.1	32.8	0.6	33.3	- 8.9	23.3	-19.4	15.0	-31.7	12.2
1968	-32.8	15.0	-27.0	17.8	-19.9	20.0	-18.9	24.4	-12.2	22.2	1.1	29.4	2.8	32.8	3.3	27.2	-2.2	28.9	- 7.2	21.7	-21.7	13.3	-38.9	7.2
1969	-38.9	6.7	-20.6	3.9	-21.1	14.4	- 4.4	22.2	- 1.1	26.1	-2.8	32.2	5.0	30.0	1.7	31.7	-2.8	31.1	-17.8	17.8	-18.3	21.7	-18.3	12.8
1970	-38.9	7.2	-22.2	14.4	-28.3	12.8	- 7.8	16.7	- 3.3	25.6	3.9	32.8	6.7	32.8	3.9	33.9	-6.7	28.3	- 9.4	27.8	-26.7	13.3	-32.8	5.0
1971	-36.1	10.0	-28.9	10.0	-23.3	8.3	- 8.3	20.6	- 2.2	27.2	2.2	26.1	1.1	30.6	5.6	30.0	-3.3	27.8	-17.8	25.0	-17.2	15.6	-33.3	6.7
1972	-37.8	9.9	-28.3	6.1	-34.4	16.7	-11.7	22.8	- 3.3	31.1	3.9	29.4	2.2	30.6	2.8	30.6	-6.7	22.2	-15.0	23.3	-13.9	12.2	-36.7	8.9
1973	-31.7	11.7	-28.9	11.7	-13.9	13.9	-10.6	17.2	- 5.6	27.2	0.6	30.6	3.3	32.8	0.6	31.7	-2.2	27.8	- 8.9	21.1	-29.4	6.7	-25.6	9.9
1974	-32.7	7.2	-33.9	9.4	-23.9	12.2	- 5.6	23.9	- 2.8	22.2	2.2	30.6	2.8	30.0	1.1	32.2	-6.1	27.8	- 8.3	23.9	-15.6	17.8	-19.4	12.2
1975	-35.0	11.7	-27.8	12.8	-19.4	9.4	-22.2	16.1	- 4.4	23.3	1.7	26.7	5.6	33.9	1.1	30.0	-1.7	28.9	-11.7	26.7	-23.3	22.8	-31.7	9.4
1976	-32.8	13.9	- 8.9	12.8	-32.2	15.0	- 6.7	22.2	- 1.1	27.2	0.0	26.1	4.4	29.5	3.9	30.6	0.6	28.9	-15.0	23.9	-17.8	17.8	-23.4	12.8
1977	-27.2	9.9	-33.8	13.4	-15.1	12.1	-10.3	27.8	- 0.4	23.4	0.7	33.1	3.1	30.3	1.5	24.9	-0.7	23.7	- 9.7	21.0	-27.6	11.7	-36.7	8.3
1978	-30.1	3.6	-25.1	8.5	-27.7	15.6	- 7.2	19.7	- 1.6	23.8	0.8	28.4	3.7	31.4	3.0	31.3	-0.8	27.7	- 7.3	23.9	-26.5	20.8	-30.5	8.0
1979	-32.5	5.6	-33.9	6.5	-23.1	17.7	-14.5	19.6	- 2.5	26.8	-0.3	29.9	2.9	34.3	4.3	18.4	-0.5	30.6	-11.7	27.9	-18.6	19.0	-33.1	12.7
1980	-32.1	10.2	-27.2	8.7	-24.2	10.6	- 8.7	26.3	- 1.7	27.1	3.6	25.6	4.5	29.7	-1.8	26.2	-1.1	29.7	- 9.8	28.7	-20.4	19.7	-34.1	17.4

* ^{o}C

TABLE A-9
TOTAL RAINFALL* IN CALGARY
(1956 - 1980)

YEAR	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
1956	0.0	0.0	0.5	0.8	21.6	130.6	38.6	79.2	21.1	0.3	T	0.0
1957	0.0	0.0	0.3	8.4	10.7	64.0	41.7	78.7	26.7	3.0	0.3	0.0
1958	T	T	T	11.9	15.5	96.0	60.7	17.3	56.9	2.0	0.0	T
1959	T	0.3	T	1.0	10.4	116.6	58.4	65.8	17.0	6.3	0.8	0.0
1960	0.0	0.0	0.3	T	51.8	86.1	42.7	41.7	11.7	5.8	T	T
1961	T	0.2	1.0	6.6	34.0	9.9	153.7	26.7	20.8	3.0	0.0	0.0
1962	T	T	T	T	51.6	45.2	33.0	51.3	21.6	8.1	1.3	T
1963	0.3	T	T	6.9	2.8	146.3	90.4	16.8	50.5	T	T	T
1964	T	0.5	0.0	0.3	58.7	101.6	72.1	8.1	51.3	7.1	T	0.0
1965	T	0.0	0.3	2.3	36.1	169.9	117.6	69.9	52.6	11.2	0.3	0.0
1966	0.0	5.1	T	0.8	57.7	79.2	113.3	30.5	4.6	6.9	0.5	0.0
1967	T	0.0	T	T	47.2	50.0	7.6	14.5	1.5	10.4	2.8	T
1968	T	0.0	T	T	43.9	54.9	66.5	25.7	42.9	3.3	T	0.0
1969	0.8	T	T	45.5	29.0	123.7	75.2	15.5	57.8	11.7	T	T
1970	T	0.0	0.3	T	10.7	159.0	57.4	6.6	15.2	10.9	T	0.0
1971	2.5	0.0	0.0	14.2	16.5	95.0	73.4	29.7	36.1	5.6	T	0.0
1972	0.0	T	1.3	0.5	31.0	140.5	71.4	56.4	78.7	1.5	0.3	T
1973	0.0	T	T	8.9	28.2	86.1	38.1	83.6	27.4	3.0	0.3	0.0
1974	0.0	T	T	41.1	56.4	18.8	38.4	64.0	35.3	5.8	T	0.0
1975	0.0	0.0	T	1.5	47.2	70.9	63.0	27.7	22.9	6.6	T	T
1976	0.0	T	0.8	10.4	55.9	60.2	69.6	92.5	38.1	4.1	0.3	T
1977	1.4	T	0.0	1.6	92.0	29.3	63.3	92.1	77.5	1.2	2.6	T
1978	0.7	T	0.3	45.7	75.8	59.6	55.8	104.7	82.3	7.6	T	0.0
1979	0.0	T	0.2	7.8	21.8	47.5	46.3	28.5	19.9	8.2	T	T
1980	0.3	T	0.2	3.2	95.1	103.6	50.0	31.3	41.0	16.4	0.0	0.4

* in mm; T = Traces

TABLE A-10

MECHANISMS OF CAST AND DUCTILE IRON PIPE FAILURES THROUGHOUT THE YEAR

(1979)

Month	Total Failures			Mechanical Failures			Corrosion-Related Failures		
	Cast (CI)	Ductile (DI)	Total	Cast (CI)	Ductile (DI)	Total	Cast (CI)	Ductile (DI)	Total
January	81	26	107	50	14	64	21	22	43
February	87	46	133	57	21	78	27	28	55
March	108	65	173	73	26	99	33	41	74
April	51	31	82	28	9	37	22	23	45
May	52	45	97	24	11	35	24	38	62
June	39	18	57	10	4	14	27	16	43
July	35	20	55	6	2	8	28	19	47
August	19	9	28	5	1	6	12	10	22
September	16	15	31	8	7	15	8	8	16
October	37	16	53	25	7	32	9	12	21
November	86	22	108	16	50	66	26	16	42
December	77	31	108	41	12	53	28	27	55
TOTAL	688	344	1032	343	164	507	265	260	525

TABLE A-11

MECHANISMS OF CAST AND DUCTILE IRON PIPE FAILURES THROUGHOUT THE YEAR

(1980)

Month	Total Failures			Mechanical Failures			Corrosion-Related Failures		
	Cast (CI)	Ductile (DI)	Total	Cast (CI)	Ductile (DI)	Total	Cast (CI)	Ductile (DI)	Total
January	69	41	110	57	16	73	11	26	37
February	50	38	88	37	7	44	13	31	44
March	48	34	82	26	10	36	22	24	46
April	44	35	79	19	10	29	25	25	50
May	41	27	68	12	8	20	23	25	48
June	26	22	48	9	3	12	15	21	36
July	16	20	36	1	1	2	14	20	34
August	15	27	42	3	3	6	12	24	36
September	15	19	34	6	5	11	8	15	23
October	37	18	55	20	4	24	15	16	31
November	36	25	61	26	12	38	10	13	23
December	71	33	104	45	12	57	21	26	47
TOTAL	468	339	807	261	91	352	189	266	455

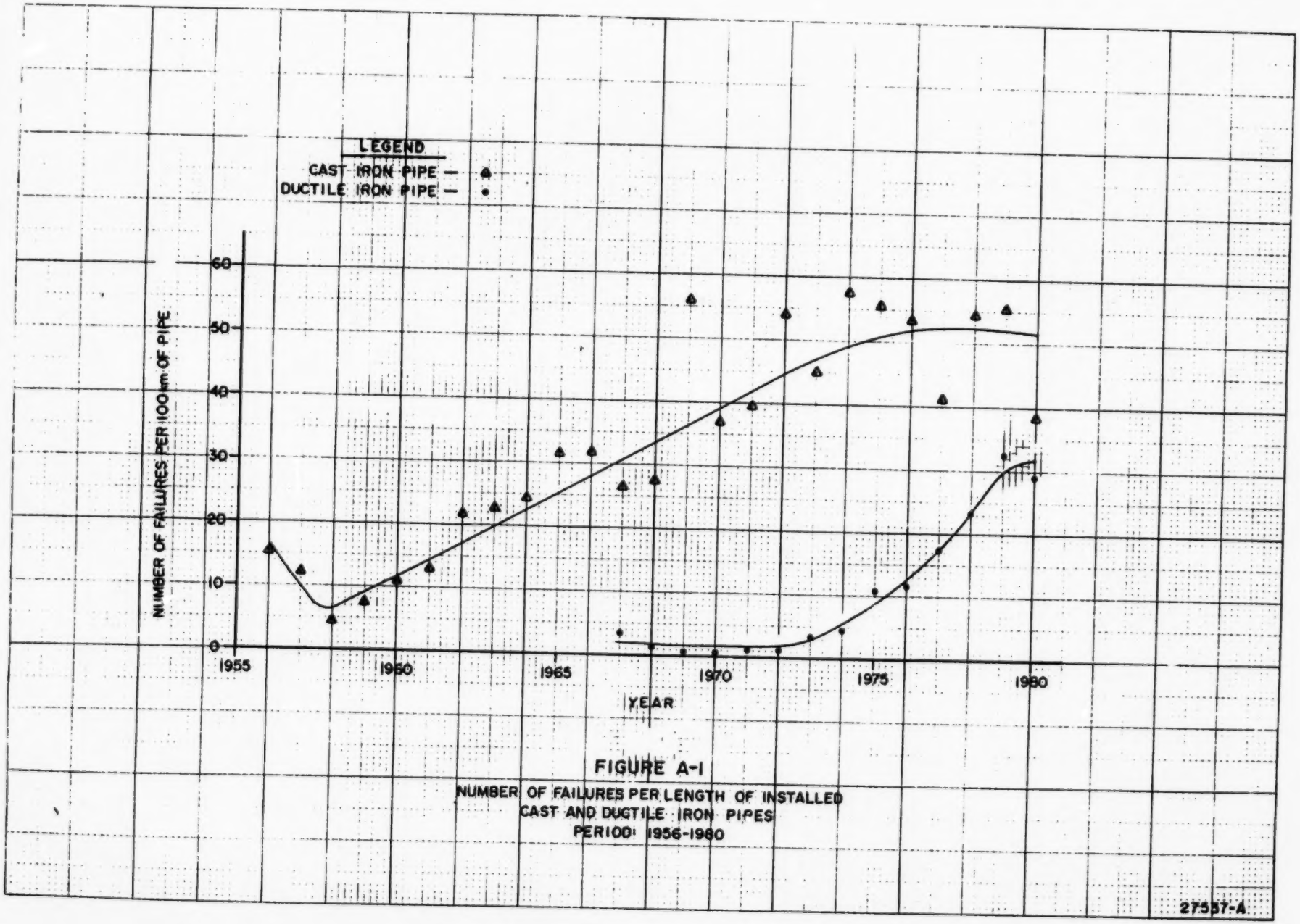

FIGURE A-1

NUMBER OF FAILURES PER LENGTH OF INSTALLED CAST AND DUCTILE IRON PIPES PERIOD: 1956-1980

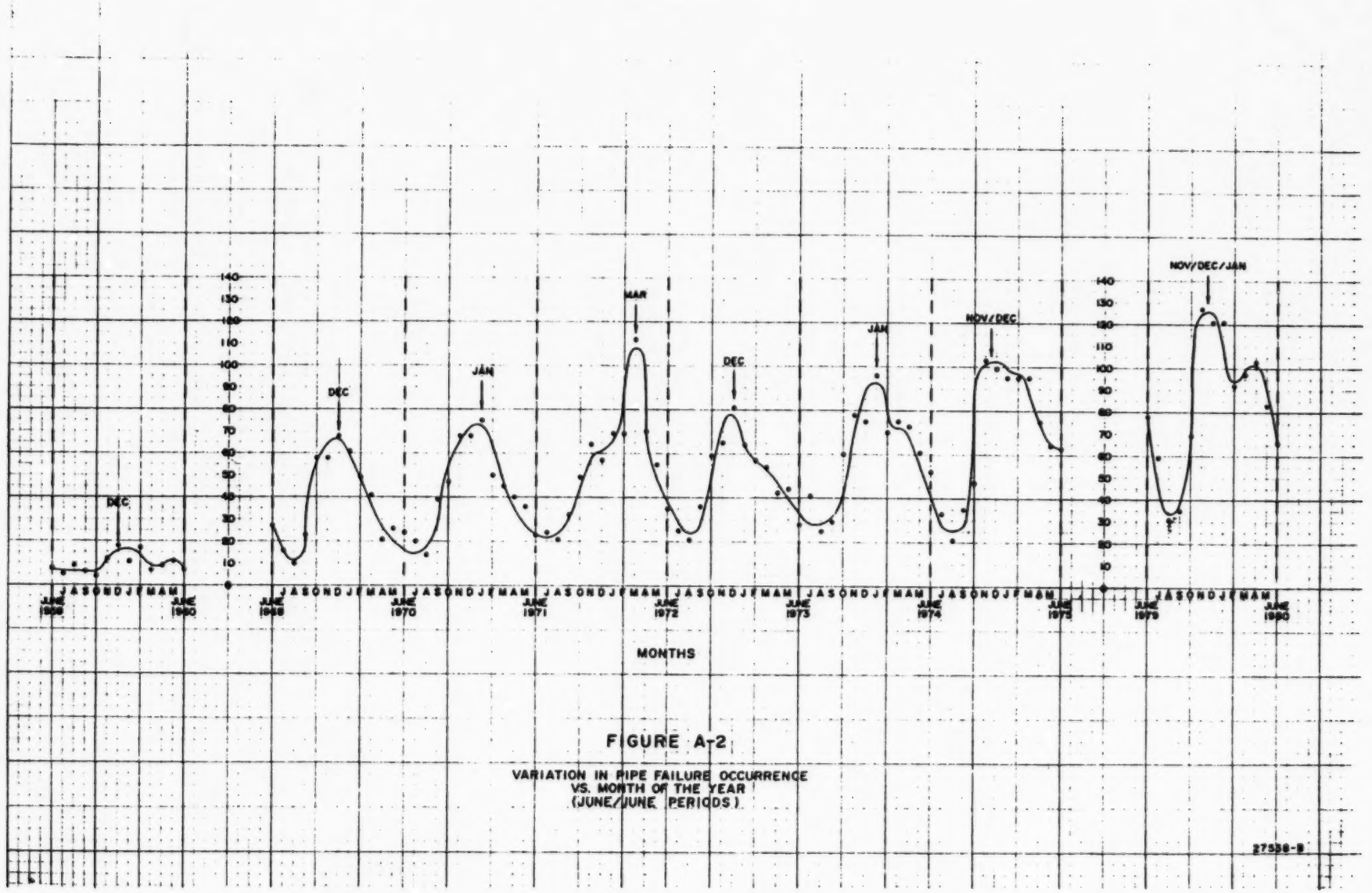

FIGURE A-2

VARIATION IN PIPE FAILURE OCCURRENCE
VS. MONTH OF THE YEAR
(JUNE/JUNE PERIODS)

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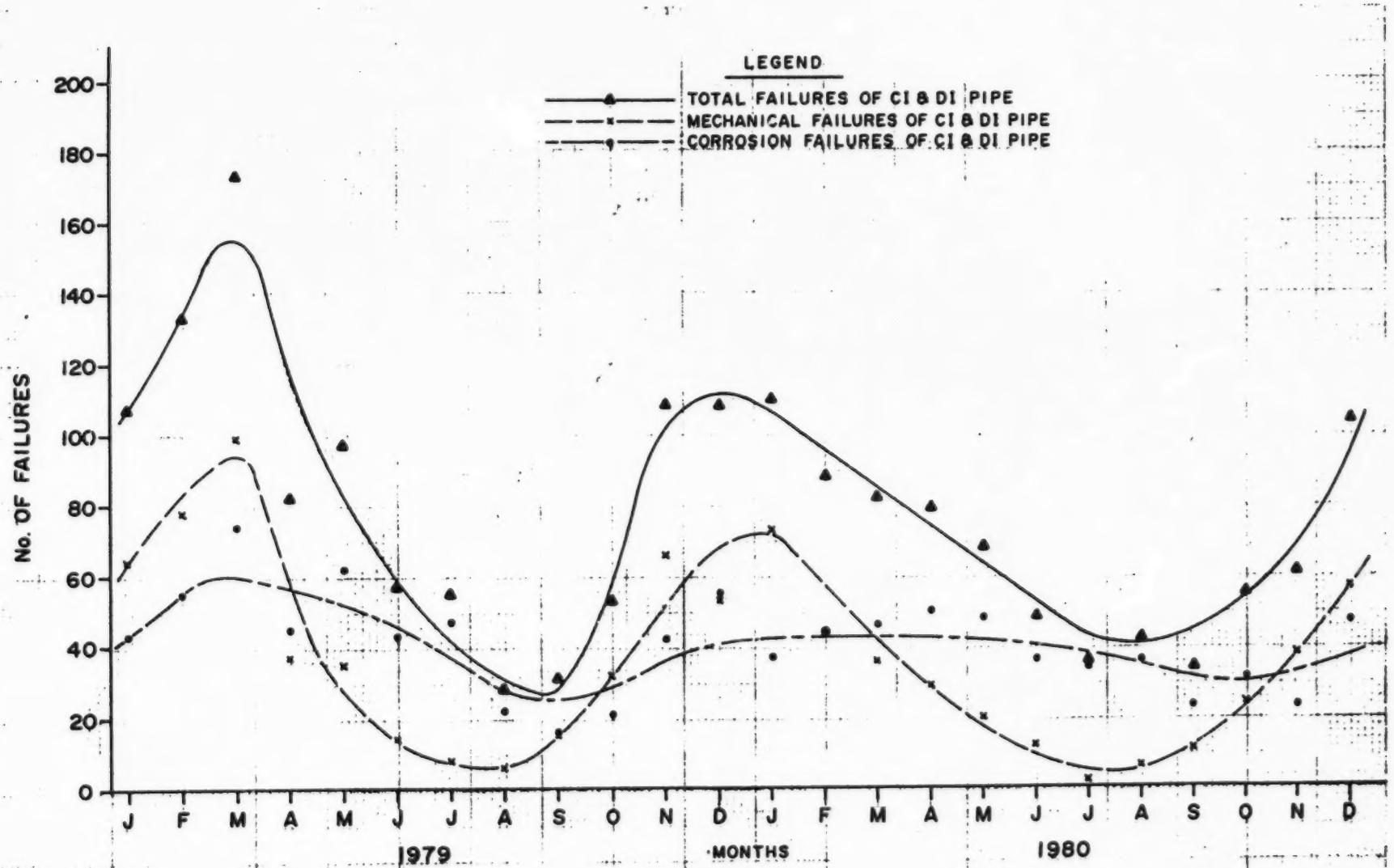

FIGURE A-3

FREQUENCY OF PIPE FAILURES THROUGHOUT THE YEAR

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APPENDIX B

EVALUATION OF MATERIAL AND ENVIRONMENT
IN CURRENT (1982 - 83) WATER MAIN FAILURES

SECTIONS

B-1 COLLECTION AND EVALUATION OF SAMPLES

B-2 TIME TO FAILURE AND PITTING CORROSION RATES

B-3 PIPE FAILURES VS MATERIAL PROPERTIES

B-4 CORROSIVITY OF SOIL

TABLES B-1 to B-9

FIGURES B-1 and B-2

B-1 COLLECTION AND EVALUATION OF SAMPLES

Samples of failed pipes and fittings evaluated in this report were from failures detected in 1982/1983 or earlier. Those which failed earlier had been temporarily fixed by clamping and left in the soil to continue service. They were collected when the mains were excavated for replacement.

All the samples were obtained between May 1982 and May 1983 along with soil sampled in the failure vicinity.

Sections of failed pipes up to 2 m long were brought to the laboratory for initial evaluation. The sections were qualitatively examined, described and photographed. Typical failures are illustrated in Appendix C.

The soil at the failure site was sampled at the main burial depth, close to the pipe. About 1000 g of soil was obtained and sealed in a heavy duty bag to prevent moisture loss. Resistivity of the samples was measured in the laboratory using a four-pin soil box* (volume = 275 cm^3) and a Nilsson-400 resistance meter.

Seventeen (17) samples as listed in Table B-1 were collected representing failures in three materials as follows:

	Number of Samples
Cast Iron Pipe (CI)	7
Ductile Iron Pipe (DI)	9
Other (Service Saddle)	1**

Ten (10) representative samples of failed pipe as indicated in Table B-1 were analyzed in detail as to metal composition, microstructure, and mechanical properties. Soil samples from the same locations were subjected to chemical and mineral analysis, and the corrosivity of each soil sample was evaluated.

The pipes were evaluated for conformance to the following specifications:

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* ASTM G-57-78 Standard Method.

** Another corroded service saddle was obtained together with Sample No. 7.

A. Cast Iron Pipes:

- pipe dimensions - tensile strength - hardness - chemical analysis	ANSI A21.6 Standard: Cast-Iron Pipe Centrifugally Cast in Metal Molds for Water or Other Liquids
- microstructure evaluation	ASTM A247 Standard: Evaluating the Microstructure of Graphite in Iron Castings

B. Ductile Iron Pipes:

- pipe dimensions - tensile strength - hardness	ANSI A21.51 Standard: Ductile-Iron Pipe Centrifugally Cast in Metal Molds or Sand-Lined Molds for Water or Other Liquids
- chemical analysis	SAE J434C Standard: Automotive Ductile (Nodular) Iron Castings
- microstructure evaluation	ASTM A247 Standard: Evaluating the Microstructure of Graphite in Iron Castings

X-ray powder diffraction analysis of corrosion products was performed for one sample only (No. 4). Presence of hydrated iron oxides, such as α-FeO (OH) and γ-FeO (OH), which are normal corrosion products of ferrous metals, was detected.

Ion content in the soil has been expressed in mg/100 g of soil while major soil mineral constituents have been given as percentages. Corrosivity was determined from soil composition and physical parameters.

B-2 TIME TO FAILURE AND PITTING CORROSION RATES

The precise date of pipe installation in the soil was available in only a few cases. For most of the failures, the date the main went into service has been used as a guide to determine the installation date.

Some of the failure samples were collected during a scheduled water main replacement, so the precise date of failure appearance (repaired by clamping on a sleeve) was not certain. In such cases the time of the pipe in soil was estimated as described in footnote* (page 3).

In Table B-2, time to failure and pipe wall thickness data permit the calculation of approximate pitting corrosion rates for most of the pipes. Soil resistivities, obtained at the failure sites, are also given.

In Table B-3 the average and extreme values of pitting corrosion rates for cast and ductile iron pipes have been summarized. Mean values calculated for both materials indicate that the corrosion rates for ductile iron pipes in Calgary soil is on the average twice as high as for cast iron pipes.

Corrosion rates for cast and ductile iron pipes have been plotted against soil resistivity at the failure locations in Figure B-1.

Despite the approximations involved in calculation of the corrosion rates, a relation between soil resistivity and the rates for both materials is obvious. When the resistivity increases, the corrosion rate declines; the decline is particularly steep for ductile iron pipes.

Cast iron pipe walls averaged about 10 mm in thickness, while ductile iron pipe walls averaged only about 7 mm in thickness. Data from Table B-2 indicates that the thicker pipe wall may have been responsible for at least a doubling of pipe service life in Calgary soil (Fig. B-2).

B-3 PIPE FAILURES VS MATERIAL PROPERTIES

Mechanical properties of the failed pipes were determined on 50 mm gauge length, 12.5 mm wide specimens of pipe wall thickness (cleaned up by machining on both sides). Results including hardness determinations are given in Table B-4. Chemical analyses of the pipe are given in Table B-5. The significance of the foregoing along with evaluations of microstructure and pipe dimensions are summarized in Table B-6.

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* In Calgary the time interval between pipe burial and putting the pipe into service varies from a few months to a few years. Two years was adopted as an average and added to the age of pipe when the exact pipe installation date was unknown. For samples obtained during scheduled replacements, it has been determined that corrosion perforation of the pipe wall took place on an average two years prior to the replacement. Consequently, two years were subtracted from the age of those pipes which have been clamped prior to the collection date.

In all cases, the dimensions of the pipes, the chemical composition, and the microstructure of the material were in accordance with the appropriate standards. However, in eight (8) out of ten (10) cases, the tensile strength of the pipes as well as the elongation when measured were below the minimum required as shown in Table B.4.

For the current (1982 - 83) failures of ductile iron pipe examined, no relationship has been found between sub-standard mechanical properties and failure mechanism. Intensive localized corrosion (pitting) resulting in wall perforation was the only apparent reason for these pipe failures. However, City of Calgary records show many mechanical failures of ductile iron water pipes and it would be instructive to obtain and examine some of these.

In three (3) out of five (5) cases, the cast iron failures were attributable to corrosion pitting or graphitic corrosion of the pipes. However, in the remaining two (2) cases (Samples No. 14 and 15), the failures had a mechanical aspect which probably derived from the sub-standard mechanical properties of the material. Corrosion, however, was the major failure mode in these pipes.

In summary, in eight (8) out of the ten (10) samples of failed pipes investigated in detail, corrosion was solely responsible for the failure. In the remaining two samples, both corrosion and mechanical mechanisms were operative.

B-4 CORROSIVITY OF SOILS

Corrosivity of soil samples taken at failure sites was evaluated on the basis of various physical parameters and chemical analyses. This data is summarized in Table B-7.

Criteria for corrosivity classification were adopted after Baeckmann and Schwenk*, as given in Tables B-8 and B-9.

Classification of soil samples based on the above criteria is presented in Table B-9.

Soil from all locations falls into the category "Corrosive", except for soil sample No. 13, which is rated "Very Corrosive."

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* W.v. Baeckmann, W. Schwenk, Handbook of Cathodic Protection, Portcullis Press, 1975, Chapter II.4.

TABLE B-1

LIST OF COLLECTED SAMPLES

Sample Number	Type of Sample	Type of Failure	Circumstances of Failure
1+	6" CI Pipe	Corrosion perforation	Main replacement
2+	6" DI Pipe	Corrosion perforation	Main replacement
3	16" DI Pipe	Corrosion perforation	Sample not collected
4+	6" DI Pipe	Corrosion perforation	Main replacement
5	6" DI Pipe	Corrosion perforation	Main replacement
6	6" DI Pipe	Corrosion perforation	Main replacement
7	8" DI Pipe	Corrosion perforation; scattered pitting and saddle U-bolt corrosion	Main replacement
8+	8" DI Pipe	Corrosion perforation scattered pitting	Main replacement
9+	8" DI Pipe	Corrosion perforation and pitting	Old and recent failures
10	6" CI Pipe	Corrosion perforation and deep pitting	Recent failures
11+	6" DI Pipe	Corrosion perforation and pitting	Main replacement; recent failure
12	12" CI Pipe	Blown apart; graphitization	Recent failure; only pieces collected*
13+	4" CI Pipe	Corrosion perforation; scattered pitting	Main replacement; recent failure
14+	4" CI Pipe	Corrosion pitting; circular break	Recent failure
15+	8" CI Pipe	Corrosion pitting; circular break	Recent failure
16	10" Saddle	Graphitization of saddle; galvanic corrosion: copper/ bronze/steel cell	Saddle corrosion resulting in asbestos-cement water main failure
17+	8" CI Pipe	Graphitization of pipe (internal and external)	Main replacement

+ Samples analyzed in detail.
* Pipe sections with spots of graphitization were lost.

TABLE B-2

APPROXIMATE PITTING CORROSION RATES OF WATER PIPES

Sample Number	Pipe (Fitting) Material and Nominal Size	Type of Failure	Time to Failure (Years)	Wall Thickness (mm)	Resistivity of Soil[2] (ohm-cm)	Estimated Pitting Corrosion Rate (mm/y)	Remarks
1	CI, 6"	Corrosion perforation	20[1] (18-22)	10.0	1900	0.50 (0.55-0.45)	
2	DI, 6"	Corrosion perforation	9 (9-11)	6.0	1600	0.67 (0.67-0.55)	
3	DI, 16"	Corrosion perforation	10 (9-11)	~8.6	1450	0.86 (0.97-0.78)	[3]
4	DI, 6"	Corrosion perforation	6 (4- 8)	6.75	1250	1.13 (1.7 -0.84)	
5	DI, 6"	Corrosion perforation	6 (4- 8)	7.6	1450	1.27 (1.9 -0.95)	Bituminous coating internally
6	DI, 6"	Corrosion perforation	5 (3- 7)	7.5	560	1.50 (2.5 -1.07)	
7	DI, 8"	Corrosion perforation	5 (3- 7)	7.0	1200	1.40 (2.3 -1.0)	Bituminous coating over cement liner
8	DI, 8"	Corrosion perforation	5 (3- 7)	6.6	1400	1.32 (2.2 -0.94)	
9	DI, 8"	Corrosion perforation	10 (8-10)	7.4	1900	0.74 (0.93-0.62)	Bituminous coating internally
10	CI, 6"	Corrosion perforation	17 (17-19)	9.8	1600	0.58 (0.58-0.52)	Bituminous coating internally

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TABLE B-2
APPROXIMATE PITTING CORROSION RATES OF WATER PIPES
Page 2

Sample Number	Pipe (Fitting) Material and Nominal Size	Type of Failure	Time to Failure (Years)	Wall Thickness (mm)	Resistivity of Soil[2] (ohm-cm)	Estimated Pitting Corrosion Rate (mm/y)	Remarks
11	DI, 6"	Corrosion perforation	6 (4- 8)	6.65	3200	1.11 (1.66-0.83)	Bituminous coating internally
12	CI, 12"	Break; graphitic corrosion	20 (20-22)	13.3	1850	----	Bituminous coating internally
13	CI, 4"	Corrosion perforation	26	8.8	820	0.34	
14	CI, 4"	Pitting up to 60% of the wall thickness	26	9.1	4300	0.21	Bituminous coating internally
15	CI, 8"	Pitting up to 60% of the wall thickness; Crack	20	10.7	3700	0.32	
16	Copper/Bronze Steel/Cast Iron	Corrosion of service saddle	8	----	1000	----	[4])
17	CI, 8"	Local graphitic corrosion	24	11.9	2800	0.50	Bituminous coating internally

[1] Range and estimated time to failure.
[2] Silty clay or clay, all cases.
[3] Sample not collected; nominal wall thickness given.
[4] Severely corroded parts of a 10-inch service saddle on an asbestos-cement pipe.

TABLE B-3

AVERAGE AND EXTREME VALUES OF PITTING CORROSION RATES IN SOIL

Sample Number	PITTING CORROSION RATE (mm/year) Cast Iron Estimated	Cast Iron Maximum	Cast Iron Minimum	Ductile Iron Estimated	Ductile Iron Maximum	Ductile Iron Minimum
1	0.50	0.55	0.45	----	----	----
2	----	----	----	0.67	0.67	0.55
3	----	----	----	0.86	0.96	0.78
4	----	----	----	1.13	1.70	0.84
5	----	----	----	1.27	1.90	0.95
6	----	----	----	1.50	2.50	1.07
7	----	----	----	1.40	2.30	1.00
8	----	----	----	1.32	2.20	0.94
9	----	----	----	0.74	0.93	0.62
10	0.58	0.58	0.52	----	----	----
11	----			1.11	1.66	0.83
12	Graphitization (not proven by detailed evaluation - sample lost)					
13	0.34	0.34	0.34	----	----	----
14	0.21	0.21	0.21	----	----	----
15	0.32	0.32	0.32	----	----	----
16	----	----	----	----	----	----
17	0.50	0.50	0.50	(Graphitization)		----
TOTAL	2.45			10.0		
AVERAGE	0.41			1.11		

Average Pitting Corrosion Rates (mm/year):

Cast Iron	0.41
Ductile Iron	1.11

TABLE B-4

MECHANICAL PROPERTIES OF THE FAILED PIPES

Sample Dia.	No.	Yield Strength (psi)	Yield Strength (MPa)	Tensile Strength (psi)	Tensile Strength (MPa)	Elongation (%) (50 mm Gauge)	Rockwell B Hardness
Cast Iron Pipes							
6"	1 a)	-	-	19900	137.3	-	84.0
	b)	-	-	24900	172.1	-	
4"	13 a)	-	-	22900	158.0		86.5
	b)	-	-	10000	69.0	-	
4"	14 a)	-	-	19900	137.0	-	85.5
	b)	-	-	15800	109.0	-	
8"	15 a)	-	-	12800	88.0	-	79.0
	b)	-	-	11900	82.0	-	
8"	17 a)	31480	217.0	31480	217.0	0.6	77.0
	b)	29500	203.0	30020	207.0	1.3	
ANSI A21.6 Standard		-	-	18000	124.1 (min)	-	95.0 (max)
Note: The standard refers to a tensile burst test which is not applicable to a section of used pipe.							
Ductile Iron Pipes							
6"	2 a)	-	-	53300	367.3	-	83.5
	b)	-	-	55900	385.3	-	
6"	4 a) (First	-	-	42000	291	-	84.0
	b) Test)	-	-	47200	326	-	
8"	4 a) (Second	44640	308	56000	386	3.5	-
	b) Test)	44700	309	54790	378	4.5	
	8 a) (First	-	-	49800	340.9	-	83.5
	b) Test)	-	-	47600	327.9	-	
	8 a) (Second	44270	305	48680	336	2.0	-
	b) Test)	44070	304	49120	339	3.0	
	9 a) (First	-	-	55900	385.2	-	88.5
	b) Test)	-	-	60700	418.8	-	

. . . 2

TABLE B-4
MECHANICAL PROPERTIES OF THE FAILED PIPES
Page 2

Sample Dia.	No.	Yield Strength (psi)	(MPa)	Tensile (psi)	Strength (MPa)	Elongation (%) (50 mm Gauge)	Rockwell B Hardness
	9 a) (Second	48470	334	61175	422	4.5	-
	b) Test)	49100	339	57900	399	3.5	
	11 a)	59100	407	61300	423	3.0	88.5
	b)	46450	320	59900	413	5.0	
ANSI A21.51 Standard (Grade 60-42-10)		42000	291.0 (min)	60000	413.7 (min)	10.0 (min)	-

TABLE B-5

CHEMICAL ANALYSES OF THE FAILED PIPES

Material	Pipe No.	Wt% C	Mn	P	S	Si	Mg
Cast Iron	1	3.43	0.40	0.298	0.057	1.73	-
	13	3.55	0.53	0.447	0.057	2.85	-
	14	3.44	0.50	0.401	0.087	2.95	-
	15	2.78	0.41	0.278	0.053	2.14	-
	17	3.36	0.39	0.314	0.065	1.27	-
ANSI A21.6	-	-	-	0.9 max	0.12 max	-	-
Ductile Iron	2	3.36	0.29	0.038	0.014	2.42	0.024
	4	3.82	0.33	0.025	0.010	2.60	0.086
	8	3.75	0.28	0.040	0.008	2.71	0.030
	9	3.64	0.42	0.076	0.013	2.63	0.02
	11	3.55	0.41	0.022	0.009	3.07	0.03
SAE J434C* Standard Grade D4018	-	3.20 to 4.10	0.1 to 1.00	0.015 to 0.100	0.005 to 0.035	1.80 to 3.00	-

*ANSI A21.51 Contains no requirements for chemical analysis.

TABLE B-6

SUMMARY OF METALLURGICAL EVALUATIONS OF FAILED PIPES

No.	Sample Type	Dimensions	Conformance to Standards ANSI A21.6 - Cast Iron Pipe ANSI A21.51 - Ductile Iron Pipe[1] Tensile Strength	Hardness	Chemical Analysis	ASTM A-247 (Both Materials) Microstructure	Failure Mechanisms
1	6" CI	(+)	(+)	(+)	(+)	CI (Grey)	Pitting corrosion on soil-side; Failure not related to material deficiency.
2	6" DI	(+)	Below required minimum	[2]	(+)	DI (Ferritic)	Pitting corrosion on soil-side; Failure not related to material deficiency.
4	6" DI	(+)	Below required minimum	[2]	(+)	DI (Ferritic)	Pitting corrosion on soil-side; Failure not related to material deficiency.
8	8" DI	(+)	Below required minimum	[2]	(+)	DI (Ferritic)	Pitting corrosion on soil-side; Failure not related to material deficiency.
9	8" DI	(+)	(+) (-)[3]	[2]	(+)	DI (Ferritic)	Pitting corrosion on soil-side; Failure not related to material deficiency.
11	6" DI	(+)	(+) (-)[3]	[2]	(+)	DI (Ferritic)	Pitting corrosion on soil-side; Failure not related to material deficiency.
13	4" CI	(+)	(+) (-)[3]	(+)	(+)	CI (Grey)	Pitting corrosion on soil-side; Failure not related to material deficiency.

. . . 2

TABLE B-6
SUMMARY OF METALLURGICAL EVALUATIONS OF FAILED PIPES
Page 2

No.	Sample Type	Dimensions	Conformance to Standards ANSI A21.6 - Cast Iron Pipe ANSI A21.51 - Ductile Iron Pipe[1] Tensile Strength	Hardness[2]	Chemical Analysis	ASTM A-247 (Both Materials) Microstructure	Failure Mechanisms
14	4" CI	(+)	(+) (-)[3]	(+)	(+)	CI (Grey)	Pitting corrosion on soil-side; mechano-corrosion failure of sub-standard pipe.
15	8" CI	(+)	Below required minimum	(+)	(+)	CI (Grey)	Pitting corrosion (soil-side) with preferential attack on graphite containing regions; mechano-corrosion failure of sub-standard pipe.
16	Saddle Failure						Not subject to above standards.
17	8" CI	(+)	(+)	(+)	(+)	CI (Grey)	Severe graphitic corrosion in the form of pitting externally; moderate corrosion pitting on the water side.

[1] No requirements for chemical analysis in the standard; pipe material compared to SAE J434C, Grade D 4018.
[2] Not specified in ANSI A21.51.
[3] One sample within, the other below minimum required.
(+) Conforms to standard.
(-) Does not conform to standard.

TABLE B-7

CHEMICAL COMPOSITION AND OTHER PHYSICAL PARAMETERS OF SOIL AT FAILURE SITES

Soil Sample No.	Resistivity (ohm-cm)	pH**	Moisture Content (%)	Ion Concentration or Amount (mg/100 g of soil)								Acidity*	Alkalinity	Gravel	Sand	Clay Silt
				Cl^-	SO_4^{--}	HCO_3^-	S^{--}	Na^+	K^+	Ca^{++}	Mg^{++}					
1	1900	7.6	22.0	14.0	19.0	42	<0.1	4.5	1.2	8.0	6.0	<1	34	3	27	70
2	1600	8.2	18.1	15.0	10.0	107	<0.1	43.0	1.3	3.7	1.2	<1	83	3	31	66
4	1250	8.2	15.9	8.0	55.0	30	<0.1	9.0	2.3	16.0	8.0	<1	24	4	28	68
8	1400	7.7	17.8	4.0	38.0	44	<0.1	10.5	1.5	11.0	8.5	<1	36	0	15	85
9	1900	7.8	16.3	3.0	12.0	51	<0.1	19.0	1.2	3.9	3.1	<1	42	0	7	93
11	3200	8.2	16.7	2.5	4.0	49	<0.1	4.6	1.2	4.2	7.4	<1	40	0	16	84
13	820	8.3	20.7	11.0	118.0	43	<0.1	16.0	2.0	42.0	12.0	<1	35	8	21	71
14	4300	8.1	26.5	<1.0	2.0	43	<0.1	3.6	1.1	6.6	3.4	<1	35	1	7	92
15	3700	8.1	21.1	1.0	6.0	44	<0.1	7.4	1.5	5.0	4.1	<1	36	2	15	83
17	2800	8.0	25.2	7.5	7.5	43	<0.1	4.1	5.0	7.0	5.9	<1	35	0	40	60

* As $CaCO_3$
** 1:5 Aqua

TABLE B-8

SOIL CORROSIVITY INDEX*

		Index
1.	TYPE OF SOIL	
	- limestone	
	- marl	+2
	- marl/sand	
	- sand	
	- clay, loam	
	- marl/clay	0
	- sandy clay	
	- sandy silt	
	- silt	
	- silt/marl	-2
	- humus	
	- peat	
	- mud	-4
	- bog soil	
2.	SOIL CONDITIONS	
	Water at structure level	
	- not present	0
	- present	-1
	- variable table	-1
	- natural soil	0
	- artificial soil	-2
	- soil uniform	0
	- soil nonuniform	-3
3.	RESISTIVITY OF SOIL (ohm-cm)	
	> 10,000	0
	10,000 - 5,000	-1
	5,000 - 2,300	-2
	2,300 - 1,000	-3
	< 1,000	-4
4.	MOISTURE CONTENT	
	< 20%	0
	> 20%	-1
5.	pH	
	pH > 6	0
	pH < 6	-1
6.	TOTAL ACIDITY	
	Total acidity to pH = 7	
	< 2.5 mval/kg	0
	2.5 - 5.0 mval/kg	-1
	> 5.0 mval/kg	-2
7.	REDOX POTENTIAL	
	Parameter not measured.	
8.	TOTAL ALKALINITY	
	(As $CaCO_3$ content)	
	> 5% = 50,000 mg/kg	+2
	1-5% = 10,000 - 50,000 mg/kg	+1
	< 1% = 10,000 mg/kg	0
9.	H_2S and S^{--}	
	None	0
	< 0.5 mg/kg S^{--}	-2
	> 0.5 mg/kg S^{--}	-4
10.	COAL OR COKE	
	none	0
	present	-4
11.	CHLORIDE IONS	
	< 100 mg/kg	0
	> 100 mg/kg	-1
12.	SULPHATE IONS	
	< 200 mg/kg	0
	200 - 500 mg/kg	-1
	500 - 1000 mg/kg	-2
	> 1000 mg/kg	-3

* W.v. Baeckmann, W. Schwenk, Handbook of Cathodic Protection, Portcullis Press, 1975, Chapter II.4.

TABLE B-9

INDEXATION OF SAMPLES AND CLASSIFICATION OF SOIL CORROSIVITY*

Soil Sample No.	Type of Soil	Soil Water Table	Conditions Back-fill	Homo-geneity	Resist-ivity	Moisture Content	pH	Acidity	Alka-linity	H_2S or S^{--}	Coal (Coke)	Cl^-	SO_4^{--}	Total
1	-1	-1	0	0	-3	-1	0	-1	0	0	0	-1	0	-8
2	-1	-1	0	0	-3	0	0	-1	0	0	0	-1	0	-7
4	-1	-1	0	0	-3	0	0	-1	0	0	0	0	-2	-8
8	-1	-1	0	0	-3	0	0	-1	0	0	0	0	-1	-7
9	-1	-1	0	0	-3	0	0	-1	0	0	0	0	0	-6
11	-1	-1	0	0	-2	0	0	-1	0	0	0	0	0	-5
13	-1	-1	0	0	-4	-1	0	-1	0	0	0	-1	-3	-12
14	-1	-1	0	0	-2	-1	0	-1	0	0	0	0	0	-6
15	-1	-1	0	0	-2	-1	0	-1	0	0	0	0	0	-6
17	-1	-1	0	0	-2	-1	0	-1	0	0	0	0	0	-6

CLASSIFICATION:

Total of Indexes	Soil Corrosivity
>0	Practically non-corrosive
From 0 to -4	Moderately Corrosive
From -5 to -10	Corrosive
< -10	Very Corrosive

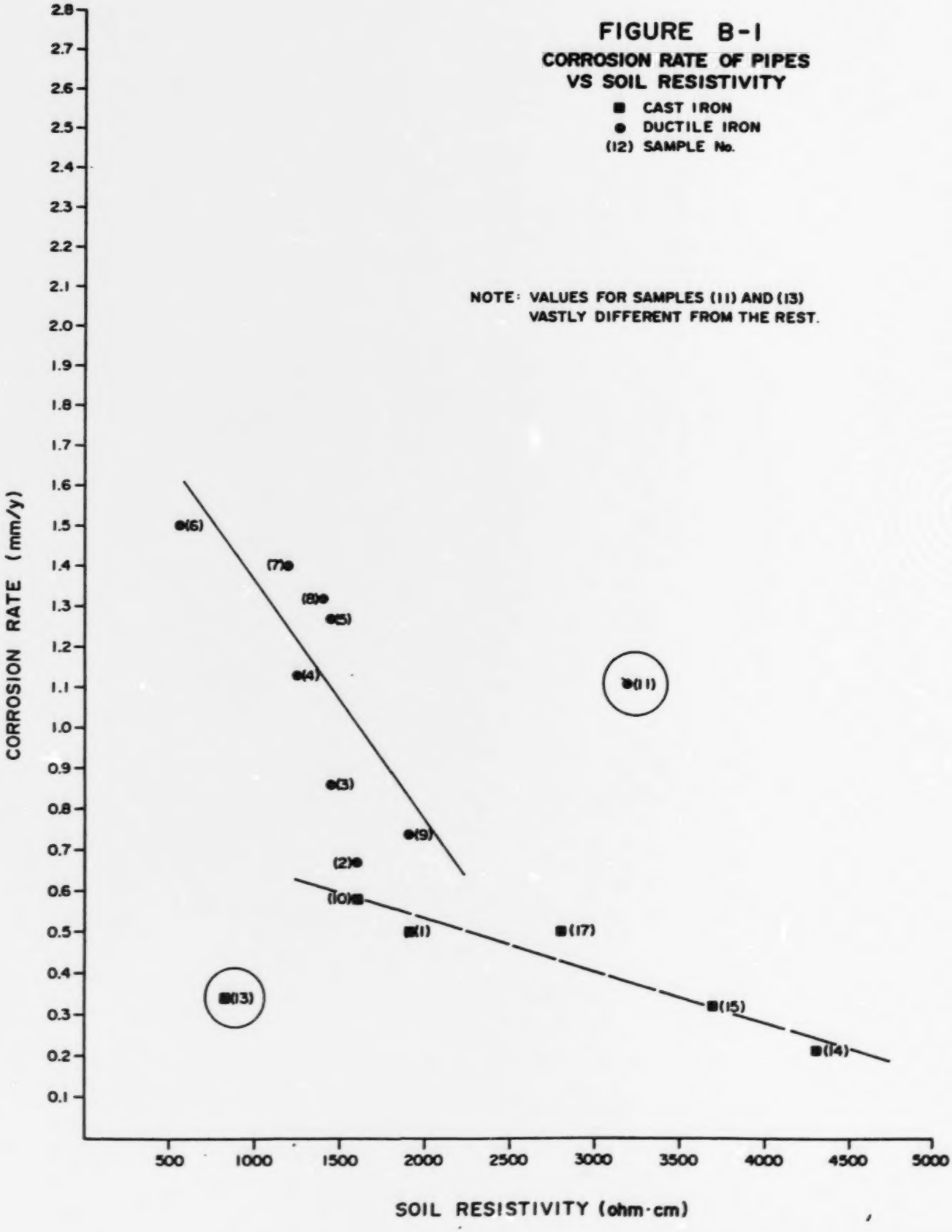
* W.v. Baeckmann, W. Schwenk, Handbook of Cathodic Protection, Portcullis Press, 1975, Chapter II.4.

FIGURE B-1

CORROSION RATE OF PIPES VS SOIL RESISTIVITY

■ CAST IRON
● DUCTILE IRON
(12) SAMPLE No.

NOTE: VALUES FOR SAMPLES (11) AND (13) VASTLY DIFFERENT FROM THE REST.



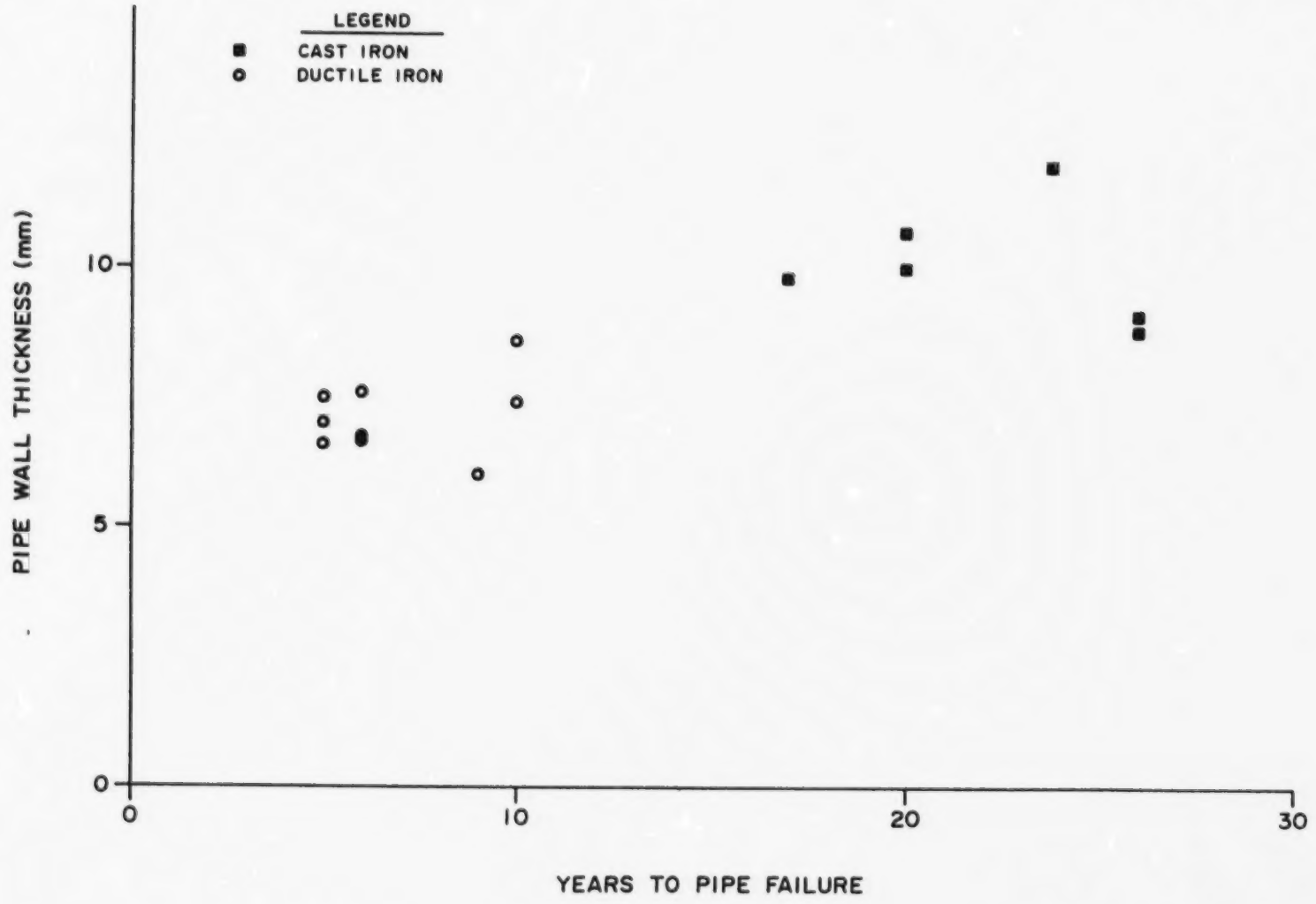


FIGURE B-2

PIPE WALL THICKNESS VS. YEARS TO PIPE FAILURE

APPENDIX C

PHOTOGRAPHS OF TYPICAL CORROSION FAILURES OF PIPES AND FITTINGS

SECTIONS

C-1 CAST IRON PIPE OD 176 mm (6") - PITTING (SAMPLE NO. 1)

C-2 CAST IRON PIPE OD 229 mm (8") - PITTING AND BREAK (SAMPLE NO. 15)

C-3 CAST IRON PIPE OD 229 mm (8") - GRAPHITIZATION (SAMPLE NO. 17)

C-4 DUCTILE IRON PIPE OD 178 mm (8") - PITTING (SAMPLE NO. 8)

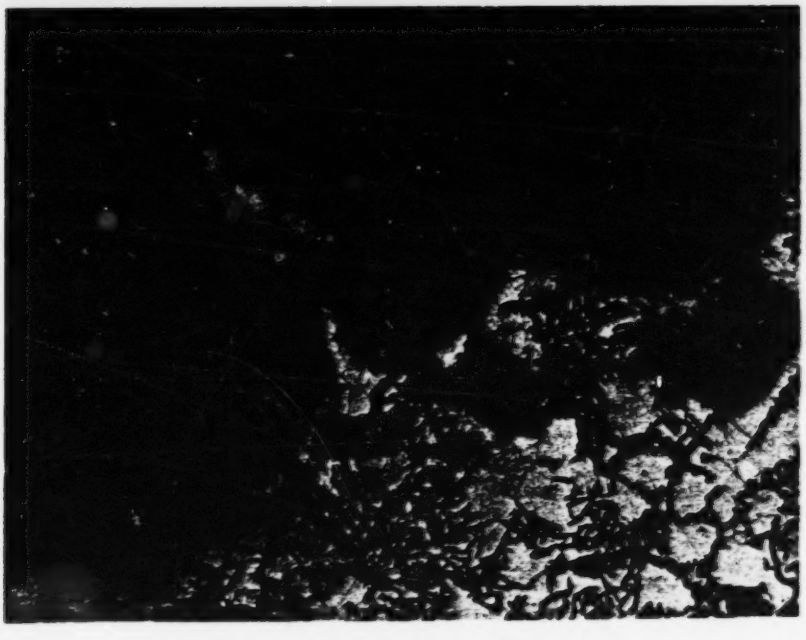
C-5 SERVICE SADDLE AND DUCTILE PIPE BY THE SADDLE - GALVANIC CORROSION (SAMPLE NO. 16; SAMPLE NO. 7)

C-6 DUCTILE IRON PIPE OD 174 mm (6") - PITTING UNDER WRAP (SAMPLE NO. 2)

C-7 PIPE FITTINGS - GALVANIC CORROSION

C-8 STAINLESS STEEL LEAK REPAIR CLAMP - GALVANIC CORROSION

a)



b)

Fig. C-1 Cast Iron Pipe OD 176 mm (6") by 10 mm W.T. (Sample No. 1)
Excavated in April 1982; approximately 20 years in soil;
a) Single large corrosion hole, approximately 5 cm in dia.
b) Pipe wall in region of failure showing pitting attack.

Fig. C-2 Cast Iron Pipe OD 229.3 mm (8") by 10.7 mm W.T. (Sample No. 15)

Excavated in November 1982; approximately 20 years in soil; Mechano-corrosion failure: pipe circular break initiated at corrosion pits;

a) As found (fitted together).

b) Corrosion pit in greater detail (pits extended more than half way through the wall).

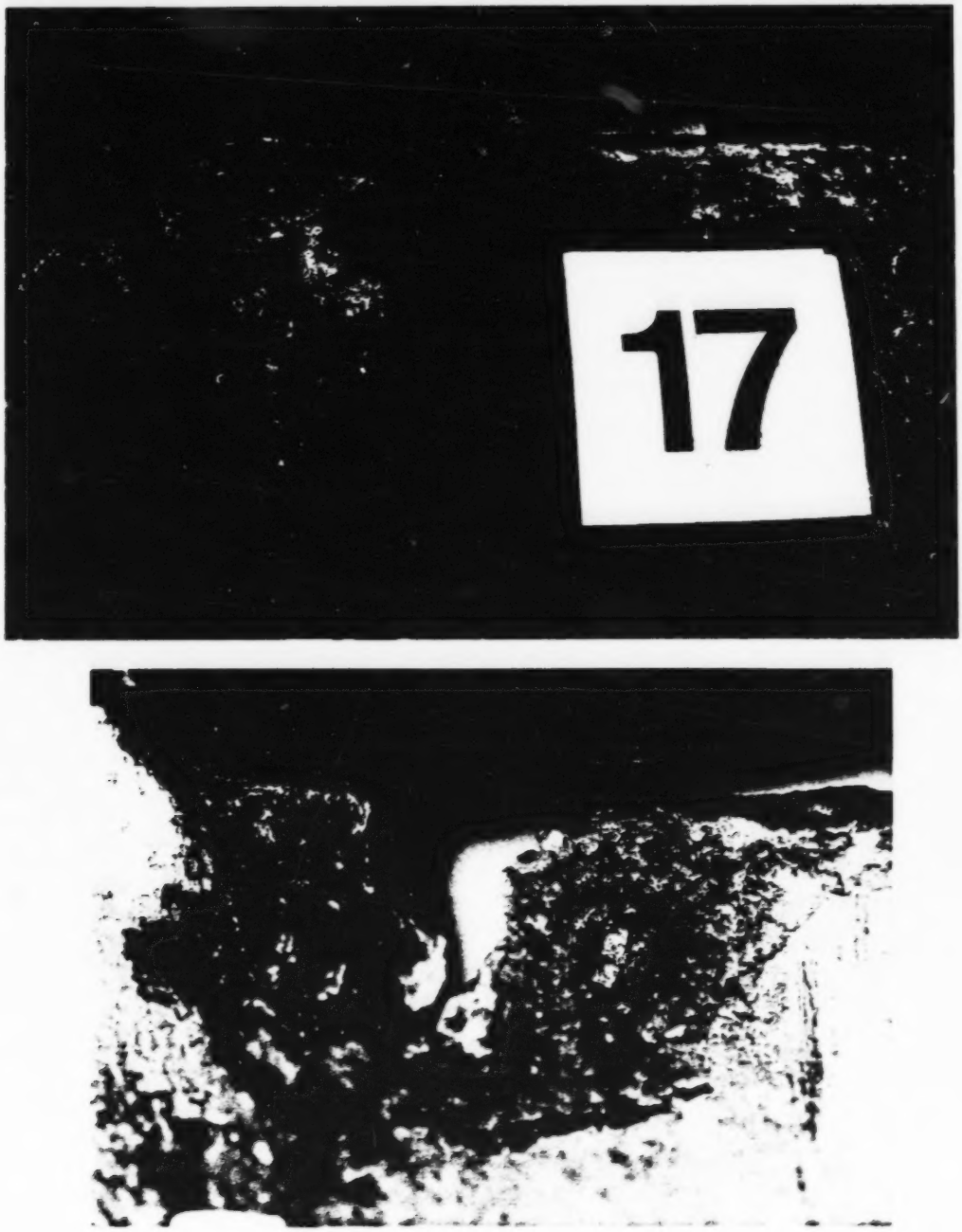


Fig. C-3 Cast Iron Pipe OD 229.1 mm (8") by 11.9 mm W.T. (Sample No. 17)

Excavated in May 1983; approximately 24 years in soil;

a) As excavated; soft spots (graphitization) beneath rust.

b) Corrosion product removed; single large corrosion hole, approximately 5 cm in dia.

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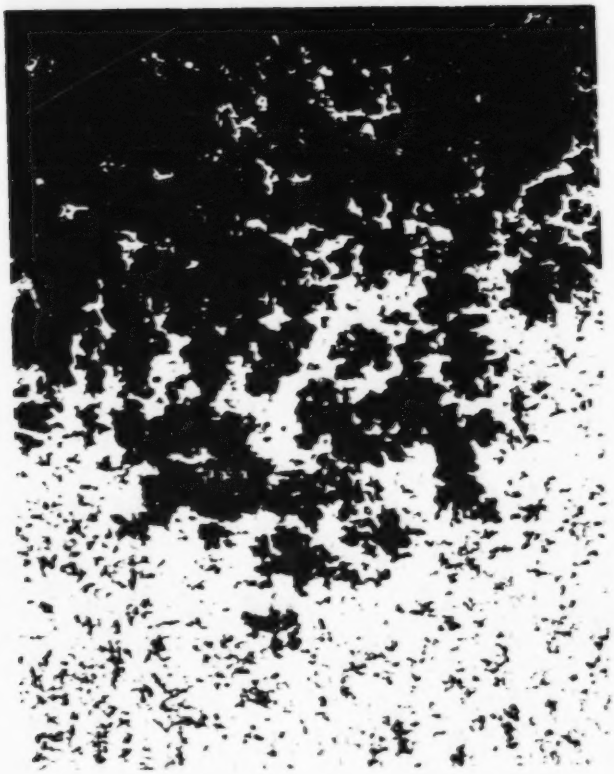

Fig. C-3 Cast Iron Pipe OD 229.1 mm (8") by 11.9 mm W.T. (Sample No. 17)

Excavated in May 1983; approximately 24 years in soil;

c) Microstructure of graphitized area.

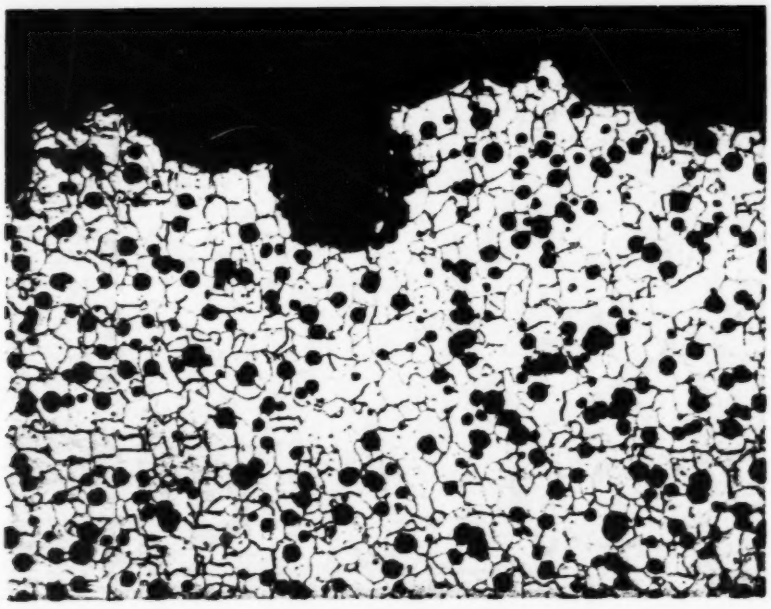

Fig. C-4 Ductile Iron Pipe OD 178 mm (6") by 6.6 mm W.T. (Sample No. 8)

Excavated in June 1982; approximately 5 years in soil;

a) Single large corrosion pit and perforation, several scattered pits in vicinity.

b) Pipe wall in region of failure showing pitting attack.

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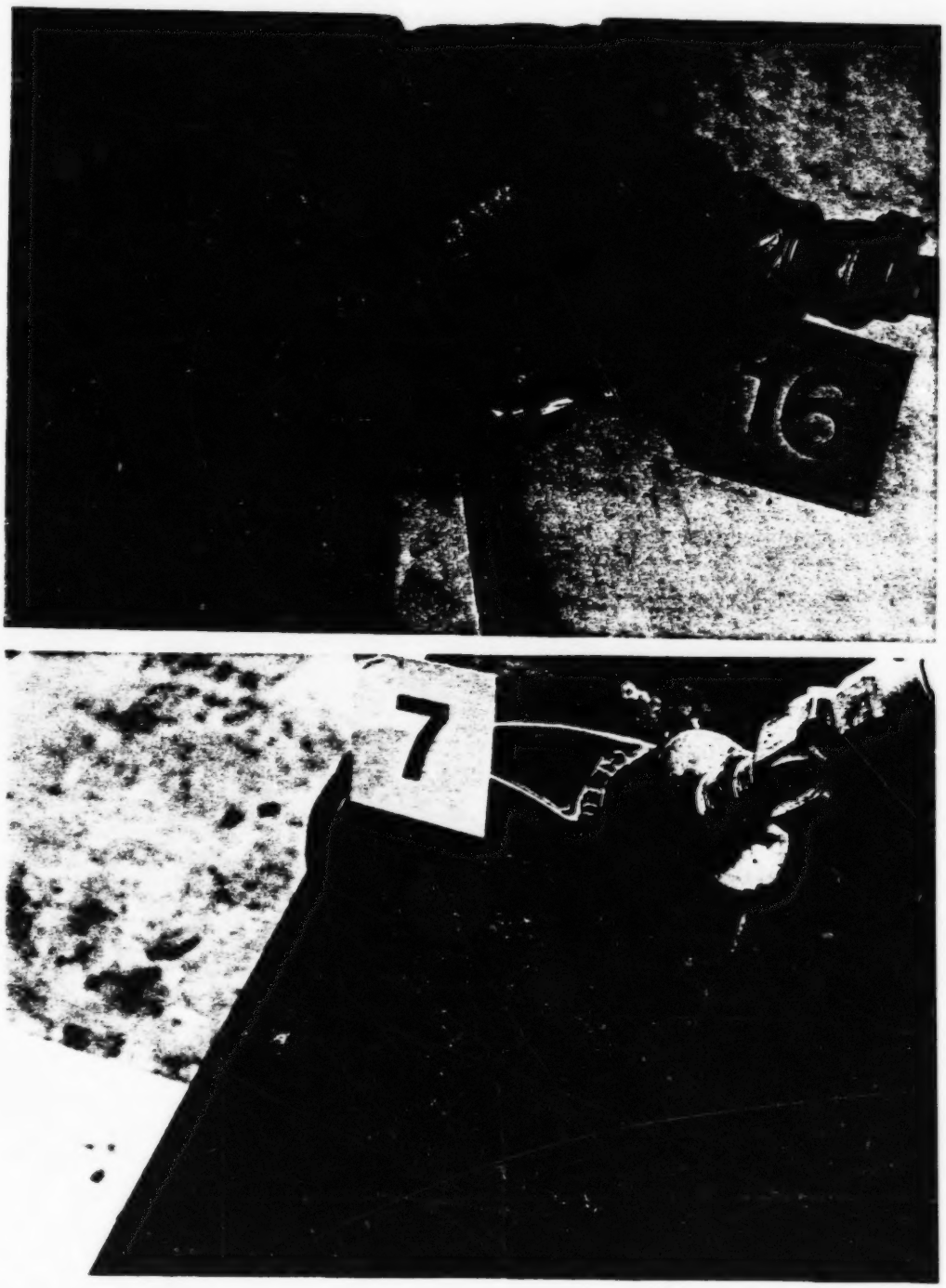

Fig. C-5 a) Severely corroded parts of a 10" service saddle installed on the asbestos-cement pipe; approximately 8 years in soil. (Sample No. 16)

b) Ductile iron pipe OD 232 mm (8") by 7.0 mm W.T.; approximately 5 years in soil; several shallow pits by the saddle. (Sample No. 7)

Fig. C-6 Ductile iron pipe OD 174 mm (6") by 6 mm W.T. (Sample No. 2)
Excavated in May 1982; approximately 9 years in soil;
Pitting corrosion under polyethylene wrap.

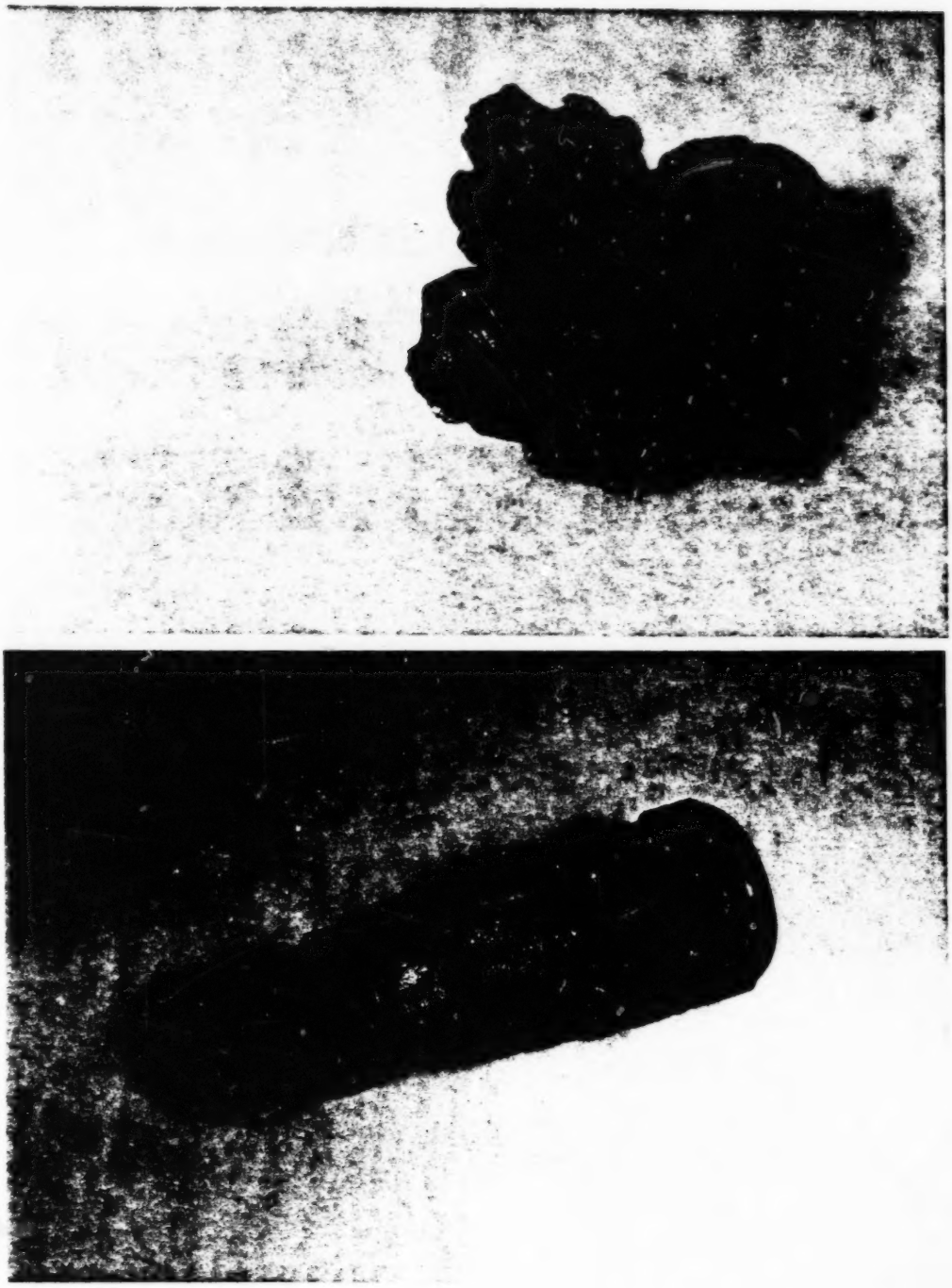

Fig. C-7 Galvanic (bimetallic) corrosion of water pipe fittings (City of Calgary collection).

a) brass valve/steel pipe: the pipe completely corroded.

b) brass fittings/cast iron reducer: the reducer corroded and perforated.

Fig. C-8 Stainless steel (304) leak repair clamp with mild steel bolts; severe galvanic corrosion of the bolts directly connected with 304 stainless steel (City of Calgary collection).

APPENDIX D

REFERENCES

SECTIONS

D-1 LITERATURE AND OTHER SOURCES

D-2 PIPE AND OTHER SPECIFICATIONS

D-3 PRODUCERS OF CAST AND DUCTILE IRON PIPES IN CANADA

D-1 LITERATURE AND OTHER SOURCES

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D-2 PIPE AND OTHER SPECIFICATIONS

Specifications directly related to or associated with the subject are listed in this section:

No.	Title	Issue and Number	Last Amendment
1.	Cast-iron pipe centrifugally cast in metal molds for water or other liquids.	ANSI A21.6-1975 CSA B131.5-1975 AWWA C106-70	*ANSI/AWWA C106-A21.6
2.	Ductile-iron pipe centrifugally cast in metal molds or sand-lined molds for water or other liquids.	ANSI A21.51-1976 CSA B131.13-1977 AWWA C151-76	*ANSI/AWWA C151/A21.51-81
3.	Gray-Iron and ductile fittings 3 inches through 48 inches for water and other liquids.	ANSI/AWWA C110-77 CSA B131.9-1978	*
4.	Automotive ductile (nodular) iron castings.	SAE J434C	-
5.	Evaluating the microstructure of graphite in iron castings.	ASTM A247	-

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No.	Title	Issue and Number	Last Amendment
6.	Polyethylene encasement for gray and ductile cast-iron piping for water and other liquids.	ANSI A21.5-1972 B131.16-1974 AWWA C105-72	*ANSI/AWWA C105/A21.5-82
7.	Field measurement of soil resistivity using the Wienner Four-Electrode method.	ASTM G57-78	-

* Canadian Standards (CSA) have been withdrawn, ANSI/AWWA Standards endorsed for use as indicated.

D-3 PRODUCERS OF CAST AND DUCTILE IRON WATER PIPES IN CANADA

There are two (2) producers of cast (grey) and ductile iron pressure pipes for water mains in Canada. The addresses of their main offices follow.

1. Canron Inc., Pipe Division
   101 Queensway West
   Mississauga, Ontario
   L5B 2P7
   (416) 276-7311

2. Stanton Pipes Ltd.
   P.O. Box 849
   Kenilworth Avenue North
   Hamilton, Ontairo
   L8N 3N9
   (416) 547-3251

Note: Canron's pipe plant in Calgary was formerly Anthes Western Ltd.

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